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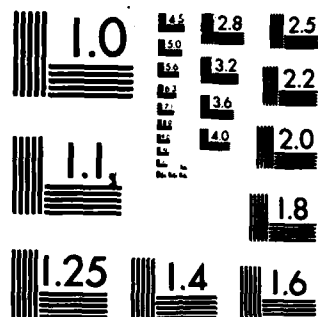
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ELECTRICAL RESISTIVITY OF ALKALINE EARTH ELEMENTS

By

T. C. CHI

CINDAS REPORT 42

December 1976

Prepared for

DEFENSE SUPPLY AGENCY
U. S. Department of Defense
Alexandria, Virginia 22304

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| REPORT DOCUMENTATION PAGE | | READ INSTRUCTIONS BEFORE COMPLETING FORM |
|--|-------------------------------------|---|
| 1. REPORT NUMBER | 2. GOVT ACCESSION NO. AD-A129038 | 3. RECIPIENT'S CATALOG NUMBER |
| 4. TITLE (and Subtitle) Electrical Resistivity of Alkaline Earth Elements | | 5. TYPE OF REPORT & PERIOD COVERED State-of-the-Art Report |
| 7. AUTHOR(s) T. C. Chi | | 6. PERFORMING ORG. REPORT NUMBER CINDAS Report 42 |
| 9. PERFORMING ORGANIZATION NAME AND ADDRESS Thermophysical and Electronic Properties Information Analysis Center, CINDAS/Purdue Univ., 2595 Yeager Rd., W. Lafayette, IN 47906 | | 8. CONTRACT OR GRANT NUMBER(s) DSA-900-76-C-0860 |
| 11. CONTROLLING OFFICE NAME AND ADDRESS Defense Technical Information Center, Defense Logistics Agency, Attn: DTIC-AI, Cameron Station, Alexandria, VA 22314 | | 10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS |
| 14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) Army Materials and Mechanics Research Center Attn: DRXMR-P Arsenal Street Watertown, MA 02172 | | 12. REPORT DATE December 1976 |
| | | 13. NUMBER OF PAGES 92 |
| | | 15. SECURITY CLASS. (of this report) Unclassified |
| | | 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE N/A |
| 16. DISTRIBUTION STATEMENT (of this Report) Distribution unlimited | | |
| 17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report) | | |
| 18. SUPPLEMENTARY NOTES (DTIC Source Code 413571); TEPIAC Publication Microfiche copies available from DTIC | | |
| 19. KEY WORDS (Continue on reverse side if necessary and identify by block number) *Electrical resistivity--- *Alkaline earth elements---*Beryllium---*Magnesium---*Calcium--- *Strontium---*Barium---*Radium | | |
| 20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This technical report presents and discusses the available data and information on the electrical resistivity of alkaline earth elements (beryllium, magnesium, calcium, strontium, barium, and radium) and contains recommended or provisional reference values. The compiled data include all the experimental data available from the literature. The temperature range covered by the compiled data is from cryogenic temperatures to above the melting temperature of the elements. The recommended values are generated from critical evaluation, analysis, and synthesis of the available data and | | |

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20. ABSTRACT (Cont)

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PREFACE

This technical report was prepared by the Thermophysical and Electronic Properties Information Analysis Center (TEPIAC), a Department of Defense Information Analysis Center. This Center is operated by the Center for Information and Numerical Data Analysis and Synthesis (CINDAS), Purdue University, West Lafayette, Indiana, under Contract No. DSA900-76-C-0860 with the Defense Supply Agency (DSA), Alexandria, Virginia, with Mr. J. L. Blue being the Program Manager, and under the technical direction of the Army Materials and Mechanics Research Center (AMMRC), Watertown, Massachusetts, with Mr. Samuel Valencia being the Contracting Officer's Technical Representative.

This report reviews the recorded world knowledge on the electrical resistivity of alkaline earth elements in a most comprehensive and detailed form making it possible for all users of the subject to have access to the original data without having to duplicate the laborious and costly process of literature search and data extraction. It is quite appropriate at this point to mention that only original sources of data have been used for the critique of the data and that all cited documents are available at CINDAS. Also, for the active researchers in the field, a detailed discussion is presented for each material, reviewing the available information together with the considerations used by the author in arriving at the final recommended reference values.

It is hoped that this work will prove useful not only to the scientists in the field but also to other engineering research and development programs and for industrial applications, as it provides a wealth of knowledge heretofore unknown or inaccessible to many. In particular, it is felt that the critical evaluation, analysis and synthesis, and reference data generation constitute a unique aspect of this work.

While this work is prepared by the staff of TEPIAC/CINDAS's Reference Data Division, it would not have been possible without the direct input of TEPIAC/CINDAS' Scientific Documentation Division. Furthermore, valuable suggestions and guidance to this work have come from Dr. H. M. James and Dr. C. Y. Ho of CINDAS' senior staff.

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ABSTRACT

This technical report presents and discusses the available data and information on the electrical resistivity of alkaline earth elements (beryllium, magnesium, calcium, strontium, barium, and radium) and contains recommended or provisional reference values. . The compiled data include all the experimental data available from the literature. The temperature range covered by the compiled data is from cryogenic temperatures to above the melting temperature of the elements. The recommended values are generated from critical evaluation, analysis, and synthesis of the available data and information and are given for both the total electrical resistivity and the intrinsic electrical resistivity. For most of the elements, the recommended values cover the temperature range from 1 K to 1000 K.

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LIST OF SYMBOLS

| | |
|------------|--|
| A | Code for d. c. potentiometer method |
| B | Magnetic flux density; Code for d. c. bridge method |
| C | Code for a. c. potentiometer method; constant |
| D | Code for a. c. bridge method |
| E | Code for eddy current method |
| G | Code for galvanometer amplifier method |
| I | Code for induction method |
| L_F | Latent heat |
| M | Atomic weight |
| P | Pressure; constant |
| Q | Code for Q-meter method |
| R | Resistance |
| S_1 | Constant |
| S_2 | Constant |
| S_3 | Constant |
| T | Temperature |
| T_m | Melting point |
| T_c | Critical temperature |
| V | Voltmeter and ammeter direct reading |
| ρ | Electrical resistivity |
| ρ_0 | Residual electrical resistivity |
| ρ_i | Intrinsic electrical resistivity |
| ρ | Electrical resistivity parallel to the principal crystal-axis |
| ρ | Electrical resistivity perpendicular to the principal crystal-axis |
| θ_D | Debye temperature |
| θ_R | Empirical temperature |
| - | Code for miscellaneous methods |

1. INTRODUCTION

The purpose of this work is to present and discuss the available data and information on the electrical resistivity of alkaline earth elements, to critically evaluate, analyze, and synthesize the data, and to make recommendations for the most probable values of the electrical resistivity over a wide temperature range. Of this group of elements experimental electrical resistivity data are available in the world literature for Be, Mg, Ca, Sr, and Ba and there is no resistivity data for Ra.

Table 1 contains information on the densities, crystal structures, phase transition temperatures, and certain other pertinent physical constants of the alkaline earth elements. This information is very useful in data analysis and synthesis. For example, the electrical resistivity of a material generally changes abruptly when the material undergoes any transformation. One must, therefore, be extremely cautious in attempting to extrapolate the electrical resistivity value across any transition temperature. No attempt has been made to critically evaluate the temperatures and constants given in Table 1, and they should not be considered as recommended values.

This work is organized in six sections. In the theoretical background section, some results of the theory of electrical resistivity are presented and briefly discussed. In the section on data evaluation and generation of recommended values, the general procedures and methods for data evaluation and for the generation of recommended values are outlined.

In the data presentation section, the electrical resistivity of each of the alkaline earth elements is presented separately in the order of increasing atomic number. Values of electrical resistivities are given for both the solid and liquid states. For an element at moderate and high temperatures the true electrical resistivity values for different high-purity (99.9+) samples at each temperature should be but little different; therefore, a set of recommended electrical resistivity values can be given for a high-purity element. At low temperatures, however, the electrical resistivity values for different samples with small differences in impurity and/or imperfection differ greatly, and a set of recommended values applies only to a sample with that particular amount of impurity and imperfection. Thus, the low-temperature electrical resistivity of an element could be presented as a family of curves, each of which would be recommended for a sample with a particular amount of impurity and degree of imperfection, and hence a particular residual resistivity, ρ_0 . In this work, two well-defined curves are recommended for the full temperature range: one representing the intrinsic electrical resistivity, ρ_i , which is a unique function of temperature and is zero at absolute zero, and the other representing the total resistivity, ρ , for the purest form of each element on which measurements have

TABLE 1. PHYSICAL CONSTANTS OF ALKALINE EARTH ELEMENTS^a

| Name | Atomic No. | Atomic Weight ^b | Density ^c kg m ⁻³ × 10 ³ | Crystal Structure ^d | Phase Transition Temp., K | Debye ^e Temperature at 0 K | Melting Point, K | Normal Boiling Point, K | Critical Temp., K |
|----------------|------------|----------------------------|--|--------------------------------|---------------------------|--|------------------|-------------------------|-------------------|
| Beryllium (Be) | 4 | 9.01218 | 1.85 | c.p.h. (α) b.c.c. (β) | 1530 (α-β) | 1160 | 1562 | 2749 | 6170 |
| Magnesium (Mg) | 12 | 24.305 | 1.74 | c.p.h. | | 396±54 | 922 | 1364 | 3537 |
| Calcium (Ca) | 20 | 40.08 | 1.55 | f.c.c. (α) b.c.c. (β) | 720±2 (α-β) | 234±5 | 1113±2 | 1759 | 3273 |
| Strontium (Sr) | 38 | 87.62 | 2.60 | f.c.c. (α) b.c.c. (γ) | 830 (α-γ) | 147±1 | 1042 | 1652 | 3064 |
| Barium (Ba) | 56 | 137.4 | 3.5 | b.c.c. (α) | | 110.5±1.8 | 1002±2 | 2174 | 3670 |
| Radium (Ra) | 88 | 226.0254 | 5 | b.c.c. (α) | | 89 | 973 | 1900 | |

^a Information taken from Ref. [1].^b Atomic weights based on ¹²C = 12 as adopted by the International Union of Pure and Applied Chemistry in 1971. The number in parentheses is the mass number of the isotope of longest known half life.^c Density values given for 293 K.^d Structure below the melting temperature.^e Deduced from specific heat measurements.

been made. The latter curve at low temperatures is only applicable to the particularly characterized specimen with residual electrical resistivity clearly specified. These two curves approach each other closely, on a logarithmic scale, for temperatures above about 100 K. Figure 1 shows the relationship between ρ_i , ρ_0 , and ρ .

The recommended or provisional electrical resistivities are tabulated with uniform but step-wise increasing increments in temperature as the temperature increases. The estimated accuracy of the recommended or provisional values for each element in each different temperature range is given in the discussion. The asterisked values in the tables are interpolated, extrapolated, or estimated in the temperature ranges where no experimental data are available.

From the recommended values of ρ and ρ_i which are tabulated in this work, the electrical resistivity of a particular sample at low temperatures can be estimated in either of the following two ways. One way is to find the difference between the measured resistivity value and the recommended ρ value at the same low temperature (i.e. below 100 K) and then add this difference to the recommended ρ values at other temperatures. The second way is to compare the measured low temperature value with ρ_i , get the difference which is the residual resistivity of this particular sample, and then add this ρ_0 to the recommended ρ_i at the other temperatures.

In the figure showing experimental data, a data set that consists of a single point is denoted by a number enclosed by a square, and a curve that connects a set of data points is denoted by a ringed number. These numbers correspond to those in the data table and in the accompanying table on specimen characterization and measurement information. When several sets of data are too close together to be distinguishable, some of the data sets or data points, though listed in the table, are omitted from the figure for the sake of clarity. For all elements except francium, both logarithmic plotting and linear plotting of electrical resistivity are used in order that details may be clearly shown for both the low and high temperature regions. The recommended curves are presented in the same figure. The solid curve represents recommended values, and the dashed curves give provisional values. In the figure, the melting point (M. P.), normal boiling point (N. B. P.), and critical temperature (C. T.) of the elements are indicated. Some of these transition points are also mentioned in the text. At the melting point the resistivity exhibits large discontinuity.

The tables on specimen characterization and measurement information give for each set of data the following information: the publication reference number, author's name, year of publication, experimental method used for the measurement, temperature

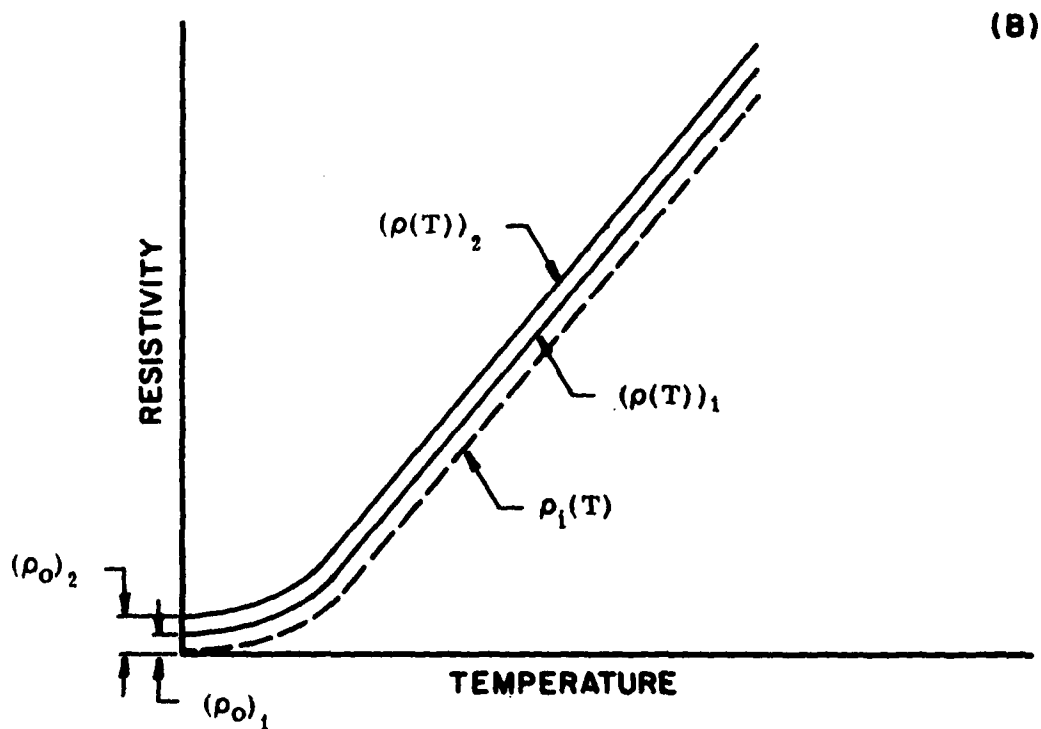
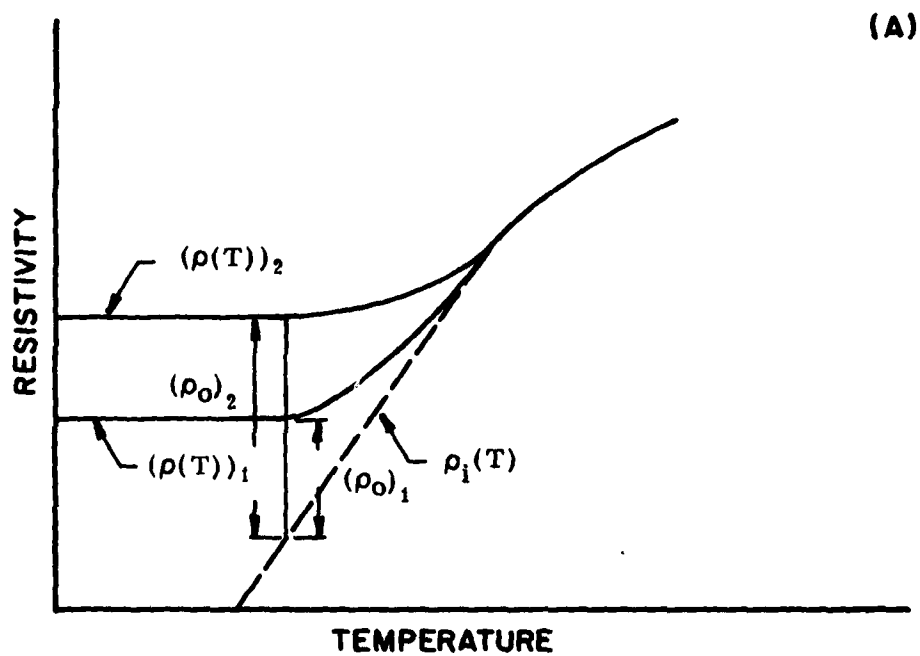


Figure 1. Relationship between intrinsic resistivity $\rho_1(T)$, residual resistivity, ρ_0 , and total resistivity, $\rho(T)$. (A) logarithm scale, (B) linear scale.

range covered by the data, substance name and specimen designation, as well as the detailed description and characterization of the specimen and information on measurement conditions that are reported in the original paper. In these tables the code designations used for the experimental methods for electrical resistivity determination are as follows:

- A D. C. Potentiometer Method
- B D. C. Bridge Method
- C A. C. Potentiometer Method
- D A. C. Bridge Method
- E Eddy Current Method
- G Galvanometer Amplifier Method
- I Induction Method
- Q Q-Meter Method
- V Voltmeter and Ameter Direct Reading
- Other than above and described in the remarks

For a comprehensive yet concise review of all these methods, the reader is referred to the references given in Appendix 7.1.

In the Thirteenth General Conference on Weights and Measures held in October 1967 in Paris, the unit "ohm-meter" (symbol: Ω m) was adopted as the SI unit for electrical resistivity. In this work, the SI units are used. Table 2 gives conversion factors which may be used to convert the electrical resistivity values in Ω m presented in this work to values in any of the several other units listed.

In the summary and conclusions section, figures are presented in which all the recommended curves on the intrinsic electrical resistivity are grouped together in order to facilitate a visual comparison.

TABLE 2. CONVERSION FACTORS FOR UNITS OF ELECTRICAL RESISTIVITY*

| MULTIPLY by appropriate factor to | | OBTAIN | | | | | |
|---|--------------------------|--------------------------|----------------------------|--------------------------|--------------------------------|---------------------------|---------------------------|
| abΩ cm | μΩ cm | Ω cm | statΩ cm | Ω m | Ω cir. mil ft ⁻¹ | Ω in. | Ω ft. |
| 1 | 0.001 | 10 ⁻⁹ | 1.113 x 10 ⁻²¹ | 10 ⁻¹¹ | 6.015 x 10 ⁻³ | 3.937 x 10 ⁻¹⁰ | 3.281 x 10 ⁻¹¹ |
| 1000 | 1 | 10 ⁻⁶ | 1.113 x 10 ⁻¹⁸ | 10 ⁻⁸ | 6.015 | 3.937 x 10 ⁻⁷ | 3.281 x 10 ⁻⁶ |
| 10 ⁹ | 10 ⁶ | 1 | 1.113 x 10 ⁻¹² | 0.01 | 6.015 x 10 ⁶ | 0.3937 | 0.0328 |
| 8.987 x 10 ²⁰ | 8.987 x 10 ¹⁷ | 8.987 x 10 ¹¹ | 1 | 8.987 x 10 ⁹ | 5.406 x 10 ¹⁸ | 3.538 x 10 ¹¹ | 2.949 x 10 ¹⁰ |
| 10 ¹¹ | 10 ⁸ | 100 | 1.113 x 10 ⁻¹⁰ | 1 | 6.015 x 10 ⁸ | 39.37 | 3.281 |
| 166.2 | 0.1662 | 1.662 x 10 ⁻⁷ | 1.850 x 10 ⁻¹⁹ | 1.662 x 10 ⁻⁹ | 1 | 6.54 x 10 ⁻⁶ | 5.45 x 10 ⁻⁶ |
| 2.54 x 10 ⁹ | 2.54 x 10 ⁶ | 2.54 | 2.827 x 10 ⁻¹² | 0.0254 | 1.528 x 10 ⁷ | 1 | 0.083 |
| 3.048 x 10 ¹⁰ | 3.048 x 10 ⁷ | 30.48 | 3.3924 x 10 ⁻¹¹ | 0.3048 | 1.833 x 10 ⁸ | 12 | 1 |

* This table is based on the universal constants from "The International System of Units (SI)," National Bureau of Standards, NBS Special Publication 330, 43 pp, 1974.

2. THEORETICAL BACKGROUND

The electrical resistivity, ρ , of a metal is often described approximately by the Matthiessen rule [2]

$$\rho(T) = \rho_0 + \rho_i(T), \quad (1)$$

where ρ_0 is the residual resistivity at absolute zero temperature and ρ_i is the intrinsic resistivity, which is the temperature-dependent resistivity of an ideally pure sample of the metal. The quantity ρ_0 arises from the presence of impurities, defects, and strains in the metal lattice, while ρ_i is caused by the interaction of the conduction electrons with the thermally induced vibrations of the lattice ions; that is, the phonons in the crystal. For a pure annealed sample at room temperature, ρ_0 is only a small fraction of the total resistivity. There are a number of mechanisms that could produce a deviation from the Matthiessen rule, resulting in a term $\Delta\rho$ appearing on the right-hand side of equation (1). The first comprehensive survey of such deviations was made by J. Bass [3]. A more recent study by Cimberle et al. [4] brings references up to date.

The intrinsic resistivity due to electron-phonon interactions may be approximated by the Bloch-Grüneisen-relation [5]

$$\rho_i(T) = \frac{C}{M \theta_R} \left(\frac{T}{\theta_R} \right)^5 \int_0^{\theta_R/T} \frac{z^5 dz}{(e^z - 1)(1 - e^{-z})}, \quad (2)$$

where C is a constant, M is the atomic weight, T is the absolute temperature, and θ_R is an empirical temperature characterizing the metal's ideal electrical resistivity in the same way that the Debye temperature, θ_D , characterizes a solid's lattice specific heat. It is often true that $\theta_R \approx \theta_D$. Below about $0.1 \theta_R$ this relation reduces to

$$\rho_i(T) \approx 124.4 \frac{C}{M} \frac{T^5}{\theta_R^5} \quad (3)$$

At high temperatures, as $T \geq \theta_R$,

$$\rho_i(T) \approx \frac{C}{4M} \frac{T}{\theta_R}. \quad (4)$$

The Grüneisen-Bloch equation is derivable only for idealized monovalent metals with Debye phonon spectra and spherical Fermi surfaces, totally neglecting the effect of Umklapp processes. However, because of its comparative simplicity, this equation is still a most valuable tool for analyzing and discussing experimental data.

The Grüneisen-Bloch equation never holds over the entire temperature range for

the alkaline earth metals. By inverting the computation, one may intercompare the behavior of different metals by interpreting the experimental results in terms of deviations from the Gruneisen-Bloch equation. This is often done by employing θ_R as a variable parameter and computing the value that it must possess at any temperature in order that the Gruneisen-Bloch equation may agree with the experiment at that temperature.

In all alkaline earth metals the electrical resistivity increases abruptly at the melting point and shows weakly negative temperature dependence in the liquid phase. The sudden change is due to the greater disorder of the liquid state and the disappearance of any definite crystal structure.

Mott [6] has presented a simple and fairly successful theory of liquid metals. He ignored the disordered positions and diffusive movements of the vibrating ions and assumed that near the melting point the ions of the liquid metal still maintain a more or less regular pattern. With an Einstein model of single frequency oscillators he obtained

$$\left(\frac{\rho_L}{\rho_S} \right)_{T_m} = \exp \left(\frac{80 L_F}{T_m} \right), \quad (5)$$

where ρ_L and ρ_S are the electrical resistivities of the liquid and solid phases, T_m is the melting point, and L_F is the latent heat of fusion in kilojoules per mole. The calculated values of $(\rho_L/\rho_S)_{T_m}$ according to this formula compare moderately well with experimental data for alkaline earth metals.

A single crystal of a metal with a cubic crystal structure has an isotropic resistivity, and the resistivity of the polycrystalline material is the same, apart from a small extra contribution in a polycrystal that may sometimes be caused by grain boundaries. But in a single crystal of noncubic metal, the resistivity is often very anisotropic, its value depending on the direction of the flow current. Likewise, polycrystalline specimens of such metals, if preferentially oriented, as by rolling or drawing, will have direction-dependent resistive properties.

In isotropic metals with the close-packed hexagonal and rhombohedral (trigonal) structures, the electrical resistivity parallel to the principal crystalline axis is designated as $\rho_{//}$ and electrical resistivity perpendicular to the principal axis is designated as ρ_{\perp} . When values for $\rho_{//}$ and ρ_{\perp} have been determined for a single crystal, one may calculate a value of ρ for a polycrystalline sample without preferential orientation by using the equation of Voigt [7]:

$$\rho = \frac{3\rho_{//} \rho_{\perp}}{2\rho_{//} + \rho_{\perp}} \quad (6)$$

Equation (6) has been used fairly commonly for the determination of ρ of a polycrystalline specimen from single crystal axial resistivities, and it usually gives satisfactory agreement with direct observation on polycrystals. However, Nichols [8] has found the relation

$$\rho = \frac{1}{3} (\rho_{//} + 2\rho_{\perp}) \quad (7)$$

to be more suitable for metals with large anisotropy ratio, and to be perfect in the case of c.p.h. Mg.

3. DATA EVALUATION AND GENERATION OF RECOMMENDED VALUES

The data analysis and synthesis employed in this work whenever possible included critical evaluation of available data and related information, reconciliation of disagreements in conflicting data, correlation of data in terms of various parameters, and curve fitting with theoretical or empirical equations. Besides critical evaluation and analysis of the existing data, semiempirical techniques have been employed to fill gaps in data and to extrapolate existing data so that the resulting recommended values are internally consistent and cover as wide a range of temperature as possible.

In the critical evaluation of the validity of electrical resistivity data, any unusual dependence or anomaly was carefully investigated, the experimental technique was reviewed to see whether the actual boundary conditions in the experiment agreed with those assumed in the theory, and the author's estimations of uncertainty were checked to ensure that all the possible sources of errors were considered. The sources of errors may have included uncertainty in the measurement of specimen dimensions and of the distance between the potential probes, uncertainty due to the effects of thermal expansion, uncertainty in temperature measurements, uncertainty in the sensitivity of measuring circuits, and so on.

Many authors have included detailed error estimates in their published papers, and from these it is possible to evaluate the uncertainty for a particular method. However, experience has shown that the uncertainty estimates of most authors are unreliable. In many cases the difference between the results of two sets of data is much larger than the sum of their stated uncertainties.

Besides evaluating and analyzing individual data sets, correlating data in terms of various relevant parameters was a valuable technique and frequently used in data analysis. These parameters may include purity, density, residual electrical resistivity and so on.

For a meaningful data correlation, information on specimen characterization is very important. A full description of the specimen should include, wherever applicable, the following: purity or chemical composition, type of crystal, crystal axis orientation for a single crystal, microstructure, grain size, preferred grain orientation, inhomogeneity or additional phases for a polycrystalline specimen, specimen shape and dimensions, method and procedure of fabrication, sample history or treatment, test environment, and pertinent physical properties such as density, hardness, and transition temperature. Data on poorly characterized materials can hardly be analyzed or used for data correlation.

Besides specimen characterization, a full description of experimental details should be given by the author in order that his data can be meaningfully evaluated and fully utilized. Sometimes, as an initial method of evaluating the quality of a paper, consideration might be given to the amount of experimental detail reported in the paper; lack of experimental detail might lead to the results being given less weight.

Our preliminary recommended values for the electrical resistivity of the alkaline earth elements were derived from experimental data that were considered reliable, using computer least-mean-square error fit to a modified Bloch-Grüneisen formula of the form

$$\rho_i(T) = [S_1 + S_2 \times (T/\theta_R) + S_3 \times (\theta_R/T)^P] \Phi(\theta_R/T) \quad (8)$$

where S_1 , S_2 and S_3 are the coefficients,

$$\theta_R = (\theta_R)_0 - CT, \quad (9)$$

$$\Phi(\theta_R/T) = 4(T/\theta_R)^5 \int_0^{\theta_R/T} \frac{z^5 dz}{(e^z - 1)(1 - e^{-z})}, \quad (10)$$

$(\theta_R)_0$, C , P , S_1 , S_2 and S_3 are used as the variable parameters.

The first term represents the basic Bloch-Grüneisen form; the second term was added in order to get better fit to high temperature data and the third term can represent a dominating low power law at very low temperatures. The computer provides a best fit to a fixed number of specified data points (T_n, ρ_n) minimizing the sum Q of the squares of the fractional errors with which ρ_n are represented by the fitting function $\rho = f(T)$. If desired, variable weights are assigned to the data points, minimizing

$$Q = \sum_n W_n [(f(T_n) - \rho_n)/\rho_n]^2 \quad (11)$$

The suitability of the form of eq. (8) has been tested by fitting it to previously smoothed data for a number of metals. The r. m. s. fractional errors in these fits were as follows:

| | | |
|----|--------------|-------|
| Li | (80-450 K), | .0024 |
| Na | (50-350 K), | .012 |
| K | (40-300 K), | .0044 |
| Rb | (30-273 K), | .012 |
| Cs | (30-273 K), | .009 |
| Cu | (60-1200 K), | .005 |
| Ag | (40-1200 K), | .004 |
| Au | (40-1200 K), | .0044 |
| Mg | (60-900 K), | .007 |

| | | |
|----|--------------|-------|
| Ca | (40-306 K), | .0056 |
| Zn | (60-600 K), | .006 |
| Al | (60-900 K), | .0033 |
| Ni | (60-600 K), | .015 |
| Fe | (80-1000 K), | .0095 |
| Pd | (80-1300 K), | .003 |

In some cases errors in the smoothing contributed to these fractional errors.

The final recommended values are obtained by extrapolating the resulting values from curve fitting values to somewhat lower and higher temperatures and correcting them for thermal linear expansion.

In estimating the uncertainty of our recommended values, the accuracy that can be achieved by the various experimental techniques, the scatter of data, and the purity of the materials, among other factors, were taken into consideration. The ranges of uncertainties of recommended and provisional values are less than or equal to $\pm 5\%$ and greater than $\pm 5\%$, respectively.

4. ELECTRICAL RESISTIVITY OF ALKALINE EARTH ELEMENTS

4.1. Beryllium

Beryllium, with atomic number 4, is a steel-gray, very hard metal, similar to magnesium in appearance and in chemical properties. It has a close-packed hexagonal crystalline structure with a density of 1.85 g cm^{-3} at 293 K. It has been reported that the crystal transforms to a body-centered cubic form at 1530 K, only 32 degrees below the melting point of 1562 K. The normal boiling point is about 2749 K. Its critical temperature has been estimated to be about 6170 K. Beryllium has only one stable isotope, ^9Be , but four other radioactive isotopes are known. Beryllium ranks 46th in the order of abundance of elements in the continental crust of the earth (0.00028% by weight).

Temperature Dependence

There are 80 sets of experimental data available for the electrical resistivity of beryllium. The information on specimen characterization and measurement conditions for each of the data sets is given in Table 4. The data are tabulated in Table 5 and shown in Figures 2 and 3. Determinations of the electrical resistivity for the solid phase cover continuously the temperature range from 1.35 to 1454 K.

Since beryllium is an anisotropic metal, resistivity values will vary according to the relation of the direction of the resistivity measurements to the hexagonal axis of the crystal. Gr \ddot{u} neisen and Adenstedt [9] (curves 16 and 17), Gr \ddot{u} neisen and Erfling [10, 11] (curves 12-14, 48-50), Martin, Bunel and Tilbury [12] (curves 59 and 60) and Mitchell [13] (curves 51 and 52) are the investigators who have made measurements on single crystals. However, their results are inconsistent and a need clearly exists for further determination to be made.

Falge [14] has found that bulk beryllium becomes superconducting when cooled below 0.026 K. Yoshihivo and Glover [15] have measured the resistivity of thin film crystalline beryllium on a quartz substrate (curve 53) and found a superconducting transition temperature at about 9.3 K. Williams, Hinkle and Eatherly [16] investigated the neutron irradiation effects on the electrical resistivity of polycrystalline beryllium samples from 72 to 400 K (curves 34-43).

Most earlier determinations of the electrical resistivity of polycrystalline beryllium resulted in higher resistivities than the later ones. These results can be explained by the lower purity of the specimens and by the omission of a heat treatment, which appears to

be essential. Powell [17] (curves 18-33) demonstrated the important effect that annealing at 973 K has on the resistivity; for his best polycrystalline specimen, ρ_{300} was lowered from 6.7 to $3.2 \times 10^{-8} \Omega \text{ m}$ by such treatment. The resistivity values obtained by Losana [18] (curves 9-11) form an anomalous group from which it would seem that the samples have much lower purity than was claimed.

From the examination of the data available for the electrical resistivity, it is evident that there are deviations from the Matthiessen's Rule. The lowest values of ρ for polycrystalline beryllium were reported by Berteaux [19] (curve 44). From his graph, we obtained $\rho_{300} = 3.0 \times 10^{-8} \Omega \text{ m}$. However, this value is lower than those for all single crystal samples with perpendicular orientation, and the reported resistance ratio $R_{300}/R_{4.2} = 49$ is inconsistent with that shown in his graph, which gives $\rho_{300}/\rho_{4.2} = 200$. Therefore, his data were not considered in the generation of recommended values. Reich, Quang, Kinch, and Boumain [20] (curve 3) and Powell [17] (curve 23) have the next lowest electrical resistivity values for polycrystalline samples, and they are in fair agreement. Comparison of their data with the single crystal data indicates that these samples had highly preferred perpendicular orientation, as is known for the sample of Reich et al. (Although Powell has annealed his sample at 973 K, this temperature was too low for sample recrystallization). The above data and the low-temperature single-crystal data of Grüneisen were used to generate provisional values for the single crystal measured perpendicular to the c-axis. A least mean-square-error fit to the selected values of $\rho - \rho_0$ was made with a modified Bloch-Grüneisen equation (8), from 20 to 873 K. The following values were found for the coefficients in equation (8):

| S_1 | S_2 | S_3 | $(\theta_R)_0$ | C | P |
|---|---|---|----------------|-------|------|
| $25.945 \cdot 10^{-8} \Omega \text{ m}$ | $-1.996 \cdot 10^{-8} \Omega \text{ m}$ | $0.3377 \cdot 10^{-8} \Omega \text{ m}$ | 1327.9 K | 0.373 | 1.90 |

The resulting values calculated from eq. (8) were extrapolated to lower and higher temperatures, corrected for thermal linear expansion, and the final provisional values were obtained.

Assuming that the anisotropy ratio of the resistivity can be used for the pure element and using the results of Grüneisen and Erfling [10] and of Mitchell [13] and the provisional values of electrical resistivity for single crystals measured perpendicular to the c-axis, the resistivity values for single crystals measured parallel to the c-axis were obtained. These values and the data of Grüneisen et al. were then fitted by the modified Bloch-Grüneisen equation (8) and the following results were obtained:

| S_1 | S_2 | S_3 | $(\theta_R)_0$ | C | P |
|---------------------------------|---------------------------------|---------------------------------|----------------|--------|------|
| $32.258 \cdot 10^{-8} \Omega m$ | $11.776 \cdot 10^{-8} \Omega m$ | $0.1815 \cdot 10^{-8} \Omega m$ | 1196.1 K | .02085 | 1.90 |

By using equation (7) and the above single-crystal results, resistivity values for the polycrystalline specimen were calculated from 10 to 1200 K. Above 1200 K, our provisional values follow the trend of the experimental data of Tye [21] (curves 63-68) and of Ho and Wright [22] (curves 73-80). These values were then fitted by the modified Bloch-Grüneisen equation (8) with the following constants:

| S_1 | S_2 | S_3 | $(\theta_R)_0$ | C | P |
|---------------------------------|---------------------------------|---------------------------------|----------------|--------|------|
| $28.117 \cdot 10^{-8} \Omega m$ | $2.0718 \cdot 10^{-8} \Omega m$ | $0.2676 \cdot 10^{-8} \Omega m$ | 1267.28 K | 0.2253 | 1.90 |

No data are available for the electrical resistivity of beryllium above the phase transition temperature (1530 K) or in the liquid state.

The provisional values for the total and intrinsic electrical resistivities are listed in Table 3, and those for the total resistivity are also shown in Figures 2 and 3. The provisional values are corrected for the thermal linear expansion. The correction amounts to -0.15% at 1 K, -0.1% at 200 K, 0.3% at 500 K, 1.3% at 1000 K and 2.4% at 1500 K. The provisional values for the total electrical resistivity are for 99.94% beryllium and those below 100 K are applicable to specimens with residual resistivities of $0.00718 \times 10^{-8} \Omega m$ (\perp to c-axis), $0.00426 \times 10^{-8} \Omega m$ (\parallel to c-axis), and $0.0332 \times 10^{-8} \Omega m$ (Polycrystalline). The uncertainty of the provisional values for the total electrical resistivity is believed to be within $\pm 8\%$ below 1000 K and within $\pm 10\%$ from 1000 K to 1500 K. Above 40 K, the uncertainty of the provisional values for the intrinsic resistivity is a little higher than that of the total electrical resistivity because of possible deviations from the Matthiessen's Rule; below 40 K the uncertainty can be very large and values are not listed in the table.

TABLE 3. PROVISIONAL ELECTRICAL RESISTIVITY OF BERYLLIUM
(Temperature Dependence)

[Temperature, T, K; Total Resistivity, ρ , $10^{-8} \Omega \text{m}$; Intrinsic Resistivity, ρ_i , $10^{-8} \Omega \text{m}$]

| T | Solid | | | | | |
|--------|-------------------|------------------|--------------|------------------|-----------------|------------------|
| | \perp to c-axis | | // to c-axis | | Polycrystalline | |
| | ρ | ρ_i^\dagger | ρ | ρ_i^\dagger | ρ | ρ_i^\dagger |
| 1 | 0.0072 | | 0.0043 | | 0.0336 | |
| 4 | 0.0072 | | 0.0043 | | 0.0332 | |
| 7 | 0.0072 | | 0.0043 | | 0.0332 | |
| 10 | 0.0072 | | 0.0043 | | 0.0332 | |
| 15 | 0.0073 | | 0.0044 | | 0.0334 | |
| 20 | 0.0076 | | 0.0046 | | 0.0336 | |
| 25 | 0.0080 | | 0.0049 | | 0.0339 | |
| 30 | 0.0086 | | 0.0054 | | 0.0345 | |
| 35 | 0.0096 | | 0.0062 | | 0.0354 | |
| 40 | 0.0109 | 0.0037 | 0.0074 | 0.0031 | 0.0367 | 0.0035 |
| 45 | 0.0127 | 0.0055 | 0.0090 | 0.0047 | 0.0384 | 0.0052 |
| 50 | 0.0150 | 0.0078 | 0.0112 | 0.0069 | 0.0407 | 0.0075 |
| 60 | 0.0218 | 0.0146 | 0.0180 | 0.0137 | 0.0675 | 0.0143 |
| 70 | 0.0325 | 0.0253 | 0.0293 | 0.0250 | 0.0584 | 0.0252 |
| 80 | 0.0483 | 0.0411 | 0.0471 | 0.0428 | 0.0748 | 0.0416 |
| 90 | 0.0711 | 0.0639 | 0.0736 | 0.0693 | 0.0989 | 0.0657 |
| 100 | 0.103 | 0.0954 | 0.111 | 0.107 | 0.133 | 0.0993 |
| 110 | 0.144 | 0.137 | 0.163 | 0.159 | 0.178 | 0.145 |
| 120 | 0.199 | 0.192 | 0.232 | 0.228 | 0.237 | 0.204 |
| 130 | 0.266 | 0.259 | 0.318 | 0.314 | 0.311 | 0.278 |
| 140 | 0.349 | 0.342 | 0.424 | 0.420 | 0.401 | 0.368 |
| 150 | 0.447 | 0.440 | 0.550 | 0.546 | 0.510 | 0.477 |
| 175 | 0.758 | 0.751 | 0.956 | 0.952 | 0.851 | 0.818 |
| 200 | 1.16 | 1.15 | 1.48 | 1.48 | 1.29 | 1.26 |
| 225 | 1.64 | 1.63 | 2.11 | 2.11 | 1.82 | 1.79 |
| 250 | 2.18 | 2.17 | 2.82 | 2.82 | 2.42 | 2.39 |
| 273.15 | 2.72 | 2.71 | 3.54 | 3.54 | 3.02 | 2.99 |
| 293 | 3.21 | 3.20 | 4.19 | 4.19 | 3.56 | 3.53 |
| 300 | 3.38 | 3.38 | 4.43 | 4.43 | 3.76 | 3.73 |
| 350 | 4.70 | 4.69 | 6.20 | 6.20 | 5.22 | 5.19 |
| 400 | 6.08 | 6.07 | 8.07 | 8.07 | 6.76 | 6.73 |
| 450 | 7.48 | 7.47 | 9.99 | 9.99 | 8.33 | 8.30 |
| 500 | 8.91 | 8.90 | 12.0 | 12.0 | 9.94 | 9.91 |
| 550 | 10.3 | 10.3 | 14.0 | 14.0 | 11.5 | 11.5 |
| 600 | 11.8 | 11.8 | 16.0 | 16.0 | 13.2 | 13.2 |

\dagger At temperatures below 40 K, the uncertainty of ρ_i is so large that values are not listed.

The provisional values for the total electrical resistivity are for 99.9+% beryllium and those below 100 K are applicable to specimens with residual resistivities of $0.00718 \times 10^{-8} \Omega \text{m}$ (\perp to c-axis), $0.00426 \times 10^{-8} \Omega \text{m}$ (\parallel to c-axis), and $0.0332 \times 10^{-8} \Omega \text{m}$ (Polycrystalline).

TABLE 3. PROVISIONAL ELECTRICAL RESISTIVITY OF BERYLLIUM (Continued)
(Temperature Dependence)

[Temperature, T, K; Total Resistivity, ρ , $10^{-8} \Omega\text{m}$; Intrinsic Resistivity, ρ_i , $10^{-8} \Omega\text{m}$]

| Solid | | | | | | |
|-------|-------------------|----------|-----------------------|----------|-----------------|----------|
| T | \perp to c-axis | | \parallel to c-axis | | Polycrystalline | |
| | ρ | ρ_i | ρ | ρ_i | ρ | ρ_i |
| 650 | 13.3 | 13.3 | 18.1 | 18.1 | 14.8 | 14.8 |
| 700 | 14.8 | 14.8 | 20.2 | 20.2 | 16.5 | 16.5 |
| 750 | 16.3 | 16.3 | 22.3 | 22.3 | 18.3 | 18.3 |
| 800 | 17.9 | 17.9 | 24.5 | 24.5 | 20.0 | 20.0 |
| 850 | 19.5 | 19.5 | 26.7 | 26.7 | 21.8 | 21.8 |
| 900 | 21.1 | 21.1 | 28.9 | 28.9 | 23.7 | 23.7 |
| 950 | 22.7 | 22.7 | 31.2 | 31.2 | 25.6 | 25.6 |
| 1000 | 24.4 | 24.4 | 33.5 | 33.5 | 27.5 | 27.5 |
| 1100 | 27.8 | 27.8 | 38.3 | 38.3 | 31.5 | 31.5 |
| 1200 | 31.5 | 31.5 | 43.3 | 43.3 | 35.7 | 35.7 |
| 1300 | | | | | 40.1 | 40.1 |
| 1400 | | | | | 44.8 | 44.8 |
| 1500 | | | | | 49.9 | 49.9 |

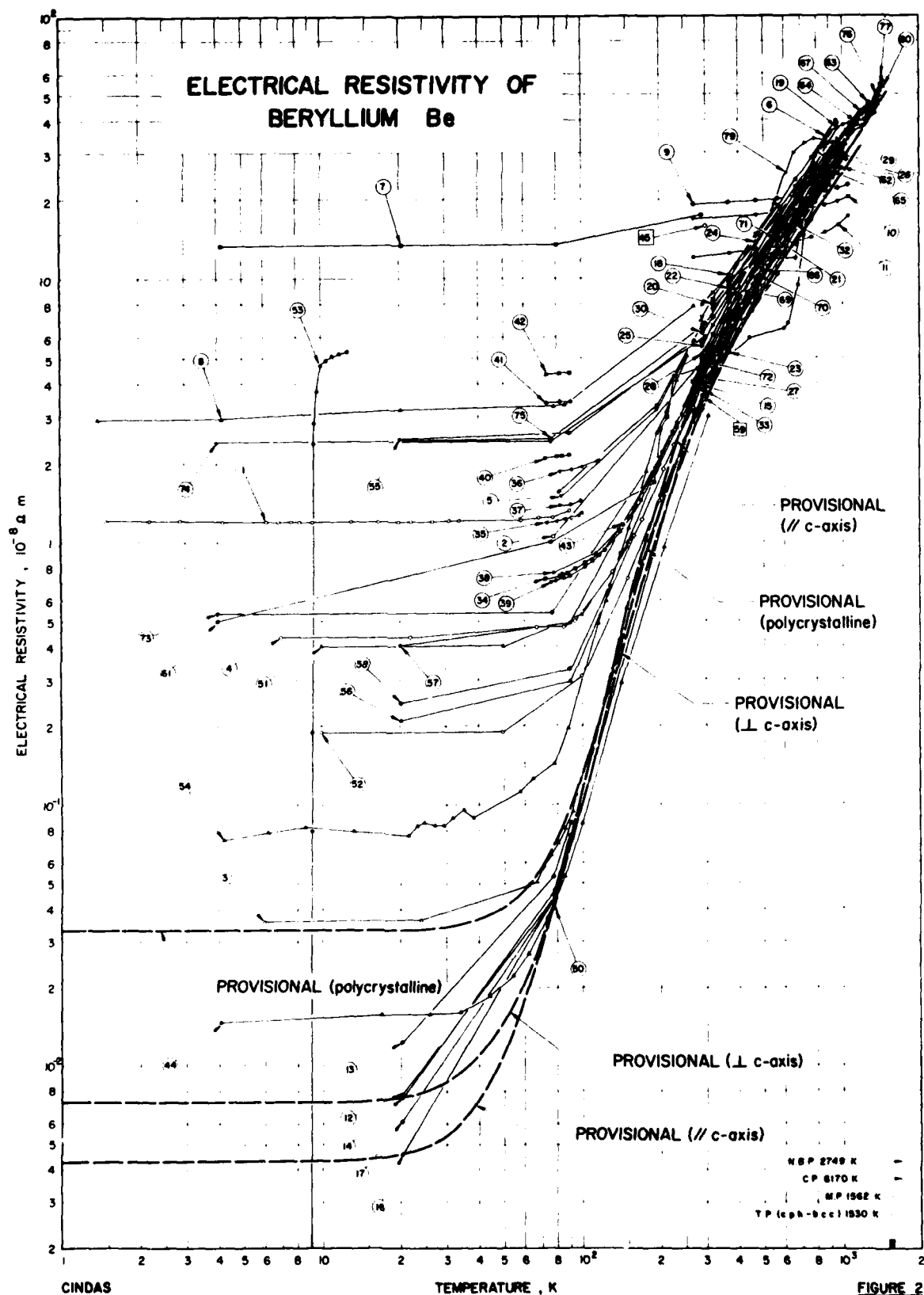


FIGURE 2

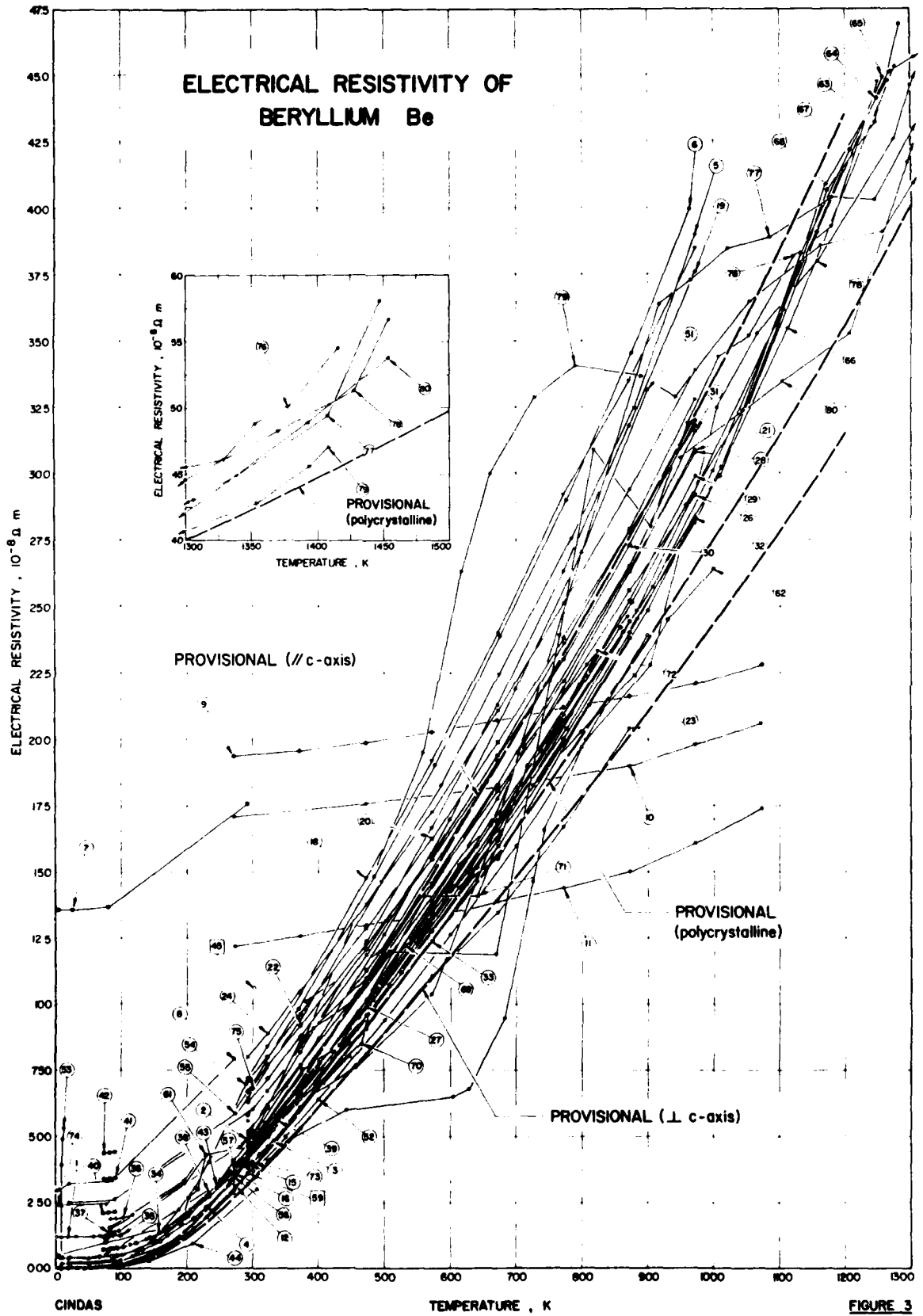


TABLE 4. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF BERYLLIUM Be (Temperature Dependence)

| Cur. Ref. No. | Author(s) | Year | Method Used | Temp. Range, K | Name and Specimen Designation | Composition (weight percent), Specifications, and Remarks |
|---------------|--|------|-------------|----------------|-------------------------------|---|
| 1 23 | White, G.K. and Woods, S.B. | 1955 | A | 2-295 | Be 2 | High purity; <0.1 Mg; trace of Fe; specimen was obtained from A.D. Mackay; sintered rod specimen, 4 mm in diameter; the connections to rods were made with indium solder. |
| 2 24 | Spangler, G.E., Herman, M., Arzuffi, E.J., Hoover, D.B., Damiano, V.V., Tim, G.S., and Lee, C.H. | 1962 | E, A | 77, 293 | Be | Commercial purity; cylindrical rod specimen 0.635 cm (1/4 in.) in diameter and 10 to 15 cm (4 to 6 in.) long. |
| 3 20 | Reich, R., Kish, V.Q., and Donmaria, J. | 1963 | | 4.2-400 | H1209 | Pure; 0.2 BeO, 0.0085 Fe, <0.003 Al, <0.001 each Ni, Cr, 0.0015 Si, and <0.0005 Mn; cast by induction; grain size 20-200 μ ; specimen was annealed at 800 C for 150 hr. |
| 4 20 | Reich, R., et al. | 1963 | | 4.2-400 | H978 | Pure; 0.1 BeO, 0.126 Fe, 0.0045 Al, 0.009 Ni, 0.002 Si, <0.001 Cr, and 0.0007 Mn; specimen was cast by induction; grain size 30-100 μ ; specimen was annealed at 800 C for 150 hr. |
| 5 25 | Lewis, E.J. | 1929 | | 84-973 | Be 1 | Commercially pure; 99.5 Be, trace of Al, Cr, Fe, Mn, Si, and <0.5 Mg; specimen was obtained from the Beryllium Co. of America; specimen cross section was 0.792 cm ² and 22.5 cm long. |
| 6 25 | Lewis, E.J. | 1929 | | 84-973 | Be 2 | Similar to the above specimen; sample cross section was 0.803 cm ² and length was 18 cm. |
| 7 26 | McLennan, J.C. and Niven, C.D. | 1927 | B | 4.2-293 | Be | Pure; specimen was obtained from Beryllium Corp. of America. |
| 8 27 | Messinger, W. and Voigt, B. | 1930 | | 1.35-273.16 | Be 3 | 0.5 Fe; specimen was prepared by melting; rod specimen dimension 1.5 x 1.5 x 8 mm; electrical resistivity data were calculated from the resistance ratio, resistance at 273.16 K, specimen cross section, and potential probes distance; no thermal expansion correction. |
| 9 18 | Losana, L. | 1939 | | 273-1073 | Be 5 | 99.58 pure, 0.21 Al, 0.182 Fe, 0.0121 Cu, trace of Ca, C, Ni; specimen was refined in beryllia crucibles under Ar atm. |
| 10 18 | Losana, L. | 1939 | | 273-1073 | Be 6 | 99.781 pure, 0.17 Al, 0.042 Fe, and 0.011 Cu; specimen was refined in beryllia crucibles under Ar atm. |
| 11 18 | Losana, L. | 1939 | | 273-1073 | Be 9 | 99.962 pure, trace of Zn, Fe; specimen was refined in beryllia crucibles under Ar atm; density 1.816 g cm ⁻³ at 291 K. |
| 12 10 | Grüneisen, E. and Erling, H.D. | 1940 | A | 20.36-273 | Be _⊥ 3 | Pure; single crystal specimen with length perpendicular to hexagonal axis; $\angle(J, X) = 12^\circ$, where $\angle(J, X)$ is the angle between the current and secondary axis. |
| 13 10 | Grüneisen, E. and Erling, H.D. | 1940 | A | 20.37-273 | Be _⊥ 4 | Pure; single crystal specimen with length perpendicular to hexagonal axis; $\angle(J, X) = 2^\circ$. |
| 14 10 | Grüneisen, E. and Erling, H.D. | 1940 | A | 20.34-273 | Be _⊥ 8 | Pure; single crystal specimen with length perpendicular to hexagonal axis; $\angle(J, X) = 30^\circ$. |
| 15 28 | Campbell, J.E., Goodwin, H.B., Wagner, H.J., Douglas, R.W., and Allen, B.C. | 1961 | | 293.15 | Be | Pure; melting point = 1350.8 K, density = 1.856 g cm ⁻³ . |
| 16 9 | Grüneisen, E. and Adenstedt, H. | 1938 | A | 20.33-273 | Be 2 | Pure; single crystal specimen with length parallel to hexagonal axis; specimen 1 mm in diameter and 1.55 cm in length; density 1.84 g cm ⁻³ . Reported error 1.5%. |
| 17 9 | Grüneisen, E. and Adenstedt, H. | 1938 | A | 20.32-273 | Be 1 | Similar to the above specimen; length 1 cm. Reported error 1.5%. |

TABLE 4. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF BERYLLIUM Be (Temperature Dependence) (continued)

| Cur. Ref. No. | Author(s) | Year | Method Used | Temp. Range, K | Name and Specimen Designation | Composition (weight percent), Specifications, and Remarks |
|---------------|--|------|-------------|----------------|-------------------------------|--|
| 18 | Powell, R.W. | 1953 | | 293-973 | Be No. B.7 (D) (i) | 96.5 Be, 1.81 Mg, 1.52 Fe, 0.55 Al, 0.035 Cu, 0.005 Mn, and 0.032 C; bar 0.5 cm square section, 13.1 cm long machined from a chilled cast bar prepared from the Brush Beryllium's crude reactor products; density 1.856. The above specimen; heat treated at 973 K. |
| 19 | Powell, R.W. | 1953 | | 293-973 | Be No. B.7 (D) (i) | |
| 20 | Powell, R.W. | 1953 | | 293-973 | Be No. B.26 (1) (ii) | Bar 2.25 cm diameter and 7.7 cm long was machined from a chilled cast bar prepared from the Brush Beryllium Company's crude reactor products; density 1.842. The above specimen; heat treated at 973 K. |
| 21 | Powell, R.W. | 1953 | | 293-973 | Be No. B.26 (1) (ii) | |
| 22 | Powell, R.W. | 1953 | | 293-973 | Be No. B.26 (2) A (iii) | Bar 0.865 cm diameter and 1.884 cm long; this had come from the same casting as No. B.26(1) bar after an attempt had been made to extrude the metal at 1000 C; subsequently the metal had been heated in vacuum for 1 hr and furnace cooled. The above specimen; heat treated at 973 K. |
| 23 | Powell, R.W. | 1953 | | 293-973 | Be No. B.26 (2) A (iii) | |
| 24 | Powell, R.W. | 1953 | | 293-973 | Be No. B.28 (2) (iv) | 98.5 Be, 0.13 Al, 0.18 Fe, 0.03 Cu, 0.05 Cl, Be insoluble in HCl 0.18; bar 2.23 cm diameter and 11.1 cm long was machined from a chilled cast bar prepared from German flake beryllium; density 1.823 g cm ⁻³ . The above specimen; heat treated at 973 K. |
| 25 | Powell, R.W. | 1953 | | 293-973 | Be No. B.28 (2) (iv) | |
| 26 | Powell, R.W. | 1953 | | 293-973 | Be No. B47B (v) | Bar 2.287 cm diameter and 15.72 cm long was machined from a chilled cast bar prepared from the Brush Beryllium Company's crude reactor product. The above specimen; heat treated at 973 K. |
| 27 | Powell, R.W. | 1953 | | 293-973 | Be No. B47B (v) | |
| 28 | Powell, R.W. | 1953 | | 293-973 | Be No. 2(b) (vi) | Bar 1.0 cm square section, 6.6 cm long; this was a block of beryllium by the "sintering" process by the American G. E. Co.; density 1.83 g cm ⁻³ . The above specimen; heat treated at 973 K. |
| 29 | Powell, R.W. | 1953 | | 293-973 | Be No. 2(b) (vi) | |
| 30 | Powell, R.W. | 1953 | | 293-973 | Be (vii) | Slice approximately 0.33 cm thick, 0.62 cm wide, and 5 cm long; density 1.85 g cm ⁻³ . The above specimen; heat treated at 973 K. |
| 31 | Powell, R.W. | 1953 | | 293-973 | Be (vii) | |
| 32 | Powell, R.W. | 1953 | | 293-973 | Be (xi) | Bar 1 in. in diameter and 6 in. long; density 1.865 g cm ⁻³ ; Mg and C main impurities, 0.34 Mg. The above specimen; heat treated at 973 K. |
| 33 | Powell, R.W. | 1953 | | 293-973 | Be (xi) | |
| 34 | Williams, J.M., Hinkle, N.E., and Eubank, W.P. | 1972 | A | 72.5-402.5 | K38-1 | Pure; specimen axis was parallel to the pressing condition. Reported error 2%. |
| 35 | Williams, J.M., et al. | 1972 | A | 73.75-100.41 | K38-1 | The above specimen; sample was irradiated by 7.41 x 10 ¹⁷ neutrons/cm ² with E > 1.0 MeV. Reported error 2%. |

TABLE 4. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF BERYLLIUM Be (Temperature Dependence) (continued)

| Cur. Ref. No. | Author(s) | Year | Method Used | Temp. Range, K | Name and Specimen Designation | Composition (weight percent), Specifications, and Remarks |
|---------------|---|------|-------------|----------------|-------------------------------|---|
| 36 | Williams, J. M., Hinkle, N. E., and Fotherly, W. P. | 1972 | A | 82.78-89.57 | K38-1 | The above specimen; sample was irradiated by 1.02×10^{15} neutrons/cm ² with $E > 1.0$ MeV. Reported error 2%. |
| 37 | Williams, J. M., et al. | 1972 | A | 82.52-117.74 | K38-1 | The above specimen; sample was irradiated by 2.15×10^{15} neutrons/cm ² with $E > 1.0$ MeV. Reported error 2%. |
| 38 | Williams, J. M., et al. | 1972 | A | 88.25-294.75 | K38-1 | The above specimen; after irradiation the sample was annealed at 324.3 K. |
| 39 | Williams, J. M., et al. | 1972 | A | 76.55-370.16 | K37-1 | Pure; specimen axis was perpendicular to the pressing condition. Reported error 2%. |
| 40 | Williams, J. M., et al. | 1972 | A | 72.91-90 | K37-1 | The above specimen; sample was irradiated by 2.53×10^{15} neutrons/cm ² with $E > 1$ MeV. Reported error 2%. |
| 41 | Williams, J. M., et al. | 1972 | A | 73.35-90 | K37-1 | The above specimen; sample was irradiated by 6.19×10^{15} neutrons/cm ² with $E > 1$ MeV. Reported error 2%. |
| 42 | Williams, J. M., et al. | 1972 | A | 73.74-92.66 | K37-1 | The above specimen; sample was irradiated by 10.53×10^{15} neutrons/cm ² with $E > 1$ MeV. Reported error 2%. |
| 43 | Williams, J. M., et al. | 1972 | A | 71.28-329.76 | K37-1 | The above specimen; after irradiation the sample was annealed at 328.6 K. |
| 44 | Berteaux, F. | 1970 | A | 4.1-307.6 | | High purity; Debye temperature $\theta = 1160$ K; data were extracted from the smooth graph. |
| 45 | Bridgman, P. W. | 1927 | A | 303 | | Pure; the specimen was a casted rod 4.6 mm in diameter and 9 cm long; the specimen was obtained from Dr. H. S. Cooper of the Kemet Laboratories; density at 293 K was found to be 1.820. |
| 46* | Babkina, M. A., Zhermumskaya, L. B., Timofeeva, Z. A., and Tsukanova, N. V. | 1972 | | ~293 | | 99.6 pure; 0.09 mm diameter wire specimen was obtained by casting, hot extrusion, and hot drawing. |
| 47* | Babkina, M. A., et al. | 1972 | | ~293 | | Similar to the above specimen; except it was tempered at 773 K. |
| 48* | Erfing, H. D. and Grünisen, E. | 1942 | A | 79-273.15 | Be // 2 | Pure; single crystal specimen with its axis parallel to hexagonal axis. |
| 49* | Erfing, H. D. and Grünisen, E. | 1942 | A | 273.15 | Be \perp 8 | Pure; single crystal specimen with its axis perpendicular to hexagonal axis. |
| 50 | Erfing, H. D. and Grünisen, E. | 1942 | A | 78-273.15 | Be // 6 | Pure; single crystal specimen with its axis parallel to hexagonal axis. |
| 51 | Mitchell, M. A. | 1975 | A | 10-900 | | Pure; single crystal specimen with its axis parallel to the hexagonal axis; sample dimension $2 \times 2 \times 19$ mm; the specimen was grown by triple zone refilling of pure Be in vacuum at the Franklin Institute Research Labs.; data are extracted from the smoothed table; reported error 1.8%. |
| 52 | Mitchell, M. A. | 1975 | A | 10-900 | | Similar to the above specimen except its axis is perpendicular to the hexagonal axis and sample dimension $4 \times 4 \times 41$ mm.; reported error 1.8%. |
| 53 | Yoshihiro, K. and Glover, R. E. III. | 1974 | A | 9.0-13 | | 99.95 pure; beryllium film were prepared by vacuum evaporation of distillation purified Be on crystalline quartz substrate; film thickness 150 Å; Ge resistance thermometer was used to measure the temperature; resistance per square data were reported; data were extracted from graph. |
| 54 | Yamaguchi, M., Takahashi, Y., Takasaki, Y., and Ohia, T. | 1974 | | 80-300 | | 0.01 Ni, 0.006 Fe, 0.003 Mn, 0.002 Al, 0.002 Mg, 0.002 Si, 0.0001 Ca, 0.0001 Na, and < 0.0001 Cu; polycrystalline specimen was obtained from Johnson Matthey Co.; $\rho_{290} = 7 \times 10^{-8}$ Ωm; data were extracted from the graph. |

* Not shown in the figure.

TABLE 4. MEASUREMENT INFORMATION OF THE ELECTRICAL RESISTIVITY OF BERYLLIUM Be (Temperature Dependence) (continued)

| Car. Ref. No. | Author(s) | Year | Method Used | Temp. Range, K | Name and Specimen Designation | Composition (weight percent), Specifications, and Remarks |
|---------------|---|------|-------------|----------------|-------------------------------|---|
| 55 | Denton, H. W. | 1947 | A | 20.2-273.2 | | Pure; cylindrical specimen 3.5 cm long and 0.3 cm in diameter was prepared by "sintering" process by the American G. E. C.; result of the x-ray examination show that the grains of order 10^{-3} cm in size, almost completely stain free, and with a small proportion of considerably smaller grains. |
| 56 | Denton, H. W. | 1947 | A | 20.2-273.2 | | Similar to the above specimen except it was annealed at 958 K for 12 hr and for shorter periods over the temperature ranges: 943 K and 833-813 K during cooling; result of x-ray examination showed the removal of any residual strain and removal of very small grains. |
| 57 | Denton, H. W. | 1947 | A | 20.2-273.2 | | Similar to the above specimen except it was further "quenched" in water from above 1023 K. |
| 58 | Denton, H. W. | 1947 | A | 20.2-273.2 | | Similar to the above specimen except it was again receiving the 958 K heat treatment. |
| 59 | Martin, A. J., Bunce, J. E., and Tutberg, P. D. | 1962 | A | 293 | 8C | Pure; 0.024 Mg, 0.003 Al, 0.037 Si, and 0.1 Fe; single crystal specimen approximately 0.5 in. in diameter and 6 in. long; crystal was extracted from stock by zone refining three times; the specimen was annealed in argon at 1153 K for 16 hr. |
| 60 | Martin, A. J., et al. | 1962 | A | 293 | 15B | Similar to the above specimen except it was zone refining twice. |
| 61 | Kuczynski, G. C. | 1960 | | 4-300 | QMV | Pure; the specimen was obtained from Brush Beryllium Corp., Cleveland, Ohio; melting point 1558 K; density 1.83 g/cm ³ ; the specimen was annealed at 973 K for 1/2 hr; data were extracted from the figure. |
| 62 | Kuczynski, G. C. | 1960 | | 270-1000 | QMV | Similar to the above specimen; the measurements were done by Battelle Institute staff; data were extracted from the figure. |
| 63 | Tye, R. P. | 1968 | | 295-1283 | Be 2 (4921) | 98.4 Be, 1.08 BeO, 0.15 C, 0.13 Fe, 0.09 Al, 0.01 Mg, 0.03 Si, 0.01 Mn, other metallic impurity 0.04; density 1.86 g/cm ³ ; hot pressed specimen is obtained from Brush Beryllium Company; cylindrical sample 13 mm in diameter and 100 mm in length; reported error 1%. |
| 64 | Tye, R. P. | 1968 | | 295-1249 | Be 4 (5085) | 98.2 Be, 1.7 BeO, 0.12 C, 0.13 Fe, 0.12 Al, 0.03 Mg, 0.04 Si, 0.01 Mn, other metallic impurity 0.04; density 1.83 g/cm ³ ; other specifications are similar to the above specimen; reported error 1%. |
| 65 | Tye, R. P. | 1968 | | 299-1258 | Be 6 (4814) | 98.46 Be, 1.6 BeO, 0.12 C, 0.12 Fe, 0.09 Al, 0.01 Mg, 0.03 Si, 0.01 Mn, other metallic impurity 0.04; density 1.86 g/cm ³ ; other specifications are similar to the above specimen; reported error 1%. |
| 66 | Tye, R. P. | 1968 | | 295-1276 | Be 8 (4814) | Similar to the above specimen; reported error 1%. |
| 67 | Tye, R. P. | 1968 | | 297-1268 | Be 9 (4811) | 98.41 Be, 1.64 BeO, 0.12 C, 0.12 Fe, 0.09 Al, 0.01 Mg, 0.03 Si, 0.01 Mn, other metallic impurity 0.04; density 1.86 g/cm ³ ; other specifications are similar to the above specimen; reported error 1%. |
| 68 | Tye, R. P. | 1968 | | 298-1266 | Be 11 (4811) | Similar to the above specimen; reported error 1%. |
| 69 | Tye, R. P. and Quinn, J. F. | 1968 | | 293-859 | Be 1 | Pure; 2 BeO, 0.15 C, 0.18 Fe, 0.08 Si, 0.08 Mg, 0.16 Al, and 0.04 other metallic impurities; specimen are obtained from Brush Beryllium Company; cylindrical specimen 13 mm in diameter and 100 mm in length. |

TABLE 4. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF BERYLLIUM Be (Temperature Dependence) (continued).

| Cat. Ref. No. | Author(s) | Year | Method Used | Temp. Range, K | Name and Specimen Designation | Composition (weight percent), Specifications, and Remarks |
|---------------|-----------------------------|------|-------------|----------------|-------------------------------|---|
| 70 | Tye, R. P. and Quinn, J. F. | 1968 | | 293-860 | Be 2 | Similar to the above specimen. |
| 71 | Tye, R. P. and Quinn, J. F. | 1968 | | 293-807 | Be 3 | Similar to the above specimen. |
| 72 | Tye, R. P. and Quinn, J. F. | 1968 | | 293-825 | Be 5 | Similar to the above specimen. |
| 73 | Ho, J. and Wright, E. S. | 1960 | B | 4-300 | T1 Y2-2 | Pure; 0.087 nonmetallic impurity, 0.094 metallic impurity; the specimens were 2 in. long and 0.1 in. by 0.5 in. rectangular bars or 0.25 in. diameter cylinders; Leeds and Northrup Precision Kelvin Bridge was used for measurements; measurements were made in vacuum. |
| 74 | Ho, J. and Wright, E. S. | 1960 | B | 4-300 | T3 Y2-3 | Pure; 0.144 nonmetallic impurity, 0.222 metallic impurity; other specifications similar to the above specimen. |
| 75 | Ho, J. and Wright, E. S. | 1960 | B | 4-300 | T3 Y2-4 | Similar to the above specimen. |
| 76 | Ho, J. and Wright, E. S. | 1960 | B | 295-1416 | Y6825 | 0.947 O, 0.0013 H, 0.0071 N, 0.003 Mg, 0.015 Al, 0.01 Si, 0.001 Ca, 0.002 Ti, 0.008 Cr, 0.005 Mn, 0.15 Fe, 0.01 Ni, and 0.004 Cu; measurements below 973 K were made in vacuum, purified argon are admitted at higher temperatures to retard the evaporation of specimen; data were extracted from the figure; other specifications are similar to the above specimens. |
| 77 | Ho, J. and Wright, E. S. | 1960 | B | 292-1447 | Y9384 | 0.54 O, 0.0106 N, 0.006 Mg, 0.05 Al, 0.008 Si, 0.002 Ca, 0.004 Ti, 0.01 Cr, 0.008 Mn, 0.15 Fe, 0.015 Ni, and 0.01 Cu; other specifications are similar to the above specimen. |
| 78 | Ho, J. and Wright, E. S. | 1960 | B | 295-1454 | Y6826 | 0.827 O, 0.0012 H, 0.0026 N, 0.01 Mg, 0.03 Al, 0.02 Si, 0.002 Ca, 0.002 Ti, 0.01 Cr, 0.006 Mn, 0.15 Fe, 0.015 Ni, and 0.01 Cu; other specifications are similar to the above specimen. |
| 79 | Ho, J. and Wright, E. S. | 1960 | B | 303-1409 | YB 1000 | 0.786 O, 0.0056 N, 0.015 Mg, 0.03 Al, 0.008 Si, 0.002 Ca, 0.002 Ti, 0.01 Cr, 0.01 Mn, 0.15 Fe, 0.02 Ni, and 0.015 Cu; other specifications are similar to the above specimen. |
| 80 | Ho, J. and Wright, E. S. | 1960 | B | 380-1454 | LYB 1102 | 0.635 O, 0.0101 H, 0.005 N, 0.02 Mg, 0.04 Al, 0.04 Si, 0.002 Ca, 0.004 Ti, 0.02 Cr, 0.008 Mn, 0.2 Fe, 0.02 Ni, and 0.01 Cu; other specifications are similar to the above specimen. |

TABLE 5. EXPERIMENTAL DATA ON THE ELECTRICAL RESISTIVITY OF BERYLLIUM Be (Temperature Dependence)

[Temperature, T, K; Resistivity, ρ , 10^{-6} Ω m]

| CURVE 1 | | CURVE 3 (cont.) | | CURVE 6 (cont.) | | CURVE 11 (cont.) | | CURVE 18 (cont.) | | CURVE 22 (cont.) | |
|---------|-----------------|-----------------|--------|-----------------|--------|------------------|---------|------------------|--------|------------------|--------|
| T | ρ | T | ρ | T | ρ | T | ρ | T | ρ | T | ρ |
| 1.5 | 1.22 | 331 | 4.83 | 777 | 29.00 | 673 | 13.9 | 373 | 10.4 | 323 | 7.7 |
| 2.5 | 1.22 | 372 | 6.07 | 877 | 34.55 | 773 | 14.4 | 473 | 14.8 | 373 | 9.2 |
| 2.9 | 1.22 | 407 | 7.12 | 963 | 40.00 | 873 | 15.0 | 573 | 19.2 | 473 | 12.3 |
| 4.2 | 1.20 | 447 | 8.17 | | | 973 | 16.1 | 673 | 24.0 | 573 | 15.5 |
| 6.2 | 1.20 | | | | | 1073 | 17.4 | 773 | 29.2 | 673 | 19.2 |
| 6.9 | 1.20 | CURVE 4 | | CURVE 7 | | CURVE 12 | | CURVE 23 | | | |
| 7.7 | 1.20 | 7 | 0.435 | 4.2 | 13.6 | 20.6 | 0.0078 | 973 | 33.5 | | |
| 8.3 | 1.20 | 22 | 0.435 | 20.6 | 13.6 | 29.36 | 0.0078 | CURVE 19 | | 293 | 3.2 |
| 9.3 | 1.20 | 67 | 0.476 | 81 | 13.7 | 78 | 0.0452 | 293 | 5.1 | 323 | 4.1 |
| 12.1 | 1.20 | 85 | 0.476 | 293 | 17.6 | 91.17 | 0.0755 | 323 | 6.2 | 373 | 5.3 |
| 16.7 | 1.20 | 94 | 0.50 | CURVE 8 | | 273.15 | 3.12 | 473 | 8.2 | 473 | 8.1 |
| 19.9 | 1.20 | 132 | 0.774 | 1.41 | 2.972 | CURVE 13 | | 573 | 11.1 | 573 | 11.1 |
| 22.3 | 1.20 | 159 | 1.06 | 4.20 | 2.972 | 20.37 | 0.0124 | 673 | 16.7 | 673 | 16.7 |
| 26.2 | 1.20 | 170 | 1.23 | 20.45 | 3.217 | 77.83 | 0.0537 | 773 | 20.3 | 773 | 20.4 |
| 31.1 | 1.22 | 209 | 1.92 | 78.42 | 3.306 | 90.35 | 0.0868 | 873 | 31.8 | CURVE 24 | |
| 34.0 | 1.22 | 229 | 2.35 | 273.16 | 7.946 | 273.15 | 3.13* | 973 | 37.6 | 293 | 8.0 |
| 58.8 | 1.22 | 269 | 3.25 | CURVE 9 | | CURVE 14 | | CURVE 20 | | 323 | 8.9 |
| 68.4 | 1.25 | 289 | 3.98 | 273 | 19.4 | 20.35 | 0.0076 | 293 | 7.1 | 373 | 10.5 |
| 77.7 | 1.25 | 309 | 4.70 | 373 | 19.6 | 78.05 | 0.0473 | 323 | 8.0 | 473 | 13.8 |
| 90.0 | 1.33 | 331 | 5.23 | 473 | 19.9 | 89.86 | 0.0770 | 473 | 9.6 | 573 | 17.3 |
| CURVE 2 | | 407 | 7.51 | 573 | 20.3 | 273.15 | 3.12* | 573 | 12.9 | 673 | 21.1 |
| 77 | 1.06 \pm 0.07 | 447 | 8.57 | 673 | 20.7 | CURVE 15 | | 673 | 16.3 | 773 | 25.1 |
| 293 | 4.90 \pm 0.07 | | | 773 | 21.2 | CURVE 16 | | 773 | 19.9 | 873 | 29.4 |
| CURVE 3 | | 84 | 1.50 | 873 | 21.6 | 283.15 | 4.0 | 873 | 23.8 | 973 | 33.9 |
| 6 | 0.026 | 196 | 3.22 | 973 | 22.1 | CURVE 17 | | 973 | 31.8 | CURVE 25 | |
| 24 | 0.0265 | 294 | 6.45 | 1073 | 22.8 | 20.33 | 0.00458 | 293 | 5.6 | 293 | 6.7 |
| 62 | 0.0495 | 381.5 | 9.75 | CURVE 10 | | 79.02 | 0.0454* | 323 | 6.4 | 373 | 9.2 |
| 67 | 0.0510 | 496 | 14.64 | 273 | 17.1 | 273.15 | 3.58 | 473 | 11.9 | 473 | 13.8 |
| 71 | 0.0535 | 588 | 18.60 | 473 | 17.6 | 20.33 | 0.00458 | 573 | 15.5* | 573 | 17.3 |
| 76 | 0.0649 | 674 | 22.45 | 573 | 18.2 | 79.02 | 0.0454* | 673 | 19.4 | 673 | 21.1 |
| 81 | 0.0719 | 785 | 27.55 | 673 | 18.2 | 273.15 | 3.58 | 773 | 23.6 | 773 | 25.1 |
| 86 | 0.0820 | 880 | 32.45 | 773 | 19.0 | CURVE 17 | | 873 | 26.3 | 873 | 29.4 |
| 92 | 0.0949 | 973 | 39.00 | 873 | 19.8 | 20.32 | 0.00616 | 973 | 30.9 | 973 | 33.9 |
| 95 | 0.111 | CURVE 5 | | 973 | 19.8 | 78.52 | 0.047* | CURVE 21 | | | |
| 122 | 0.276 | 84 | 1.50 | 1073 | 20.6 | 273.15 | 3.58* | 293 | 5.6 | 293 | 6.7 |
| 144 | 0.561 | 82 | 1.56 | CURVE 11 | | 20.33 | 0.00458 | 323 | 6.4 | 373 | 9.2 |
| 170 | 0.520 | 196 | 3.33 | 273 | 12.2 | 79.02 | 0.0454* | 473 | 11.9 | 473 | 13.8 |
| 142 | 1.01 | 295 | 6.76 | 373 | 12.6 | 273.15 | 3.58* | 573 | 15.5* | 573 | 17.3 |
| 209 | 1.52 | 370 | 9.83 | 473 | 13.0 | CURVE 18 | | 673 | 19.4 | 673 | 21.1 |
| 1.95 | 2.28 | 485 | 14.85 | 573 | 13.4 | 20.32 | 0.00616 | 773 | 23.6 | 773 | 25.1 |
| 216 | 2.70 | 578 | 19.05 | CURVE 22 | | 78.52 | 0.047* | 873 | 26.3 | 873 | 29.4 |
| 246 | 2.86 | 676 | 23.90 | 293 | 7.2 | 273.15 | 3.58* | 973 | 30.9 | 973 | 33.9 |
| 270 | 4.31 | | | 323 | 8.4 | CURVE 23 | | CURVE 26 | | | |
| 309 | | | | 293 | 6.7 | CURVE 24 | | CURVE 27 | | | |
| | | | | | | CURVE 25 | | CURVE 28 | | | |
| | | | | | | CURVE 26 | | CURVE 29 | | | |
| | | | | | | CURVE 27 | | CURVE 30 | | | |
| | | | | | | CURVE 28 | | CURVE 31 | | | |
| | | | | | | CURVE 29 | | CURVE 32 | | | |
| | | | | | | CURVE 30 | | CURVE 33 | | | |
| | | | | | | CURVE 31 | | CURVE 34 | | | |
| | | | | | | CURVE 32 | | CURVE 35 | | | |
| | | | | | | CURVE 33 | | CURVE 36 | | | |
| | | | | | | CURVE 34 | | CURVE 37 | | | |
| | | | | | | CURVE 35 | | CURVE 38 | | | |
| | | | | | | CURVE 36 | | CURVE 39 | | | |
| | | | | | | CURVE 37 | | CURVE 40 | | | |
| | | | | | | CURVE 38 | | CURVE 41 | | | |
| | | | | | | CURVE 39 | | CURVE 42 | | | |
| | | | | | | CURVE 40 | | CURVE 43 | | | |
| | | | | | | CURVE 41 | | CURVE 44 | | | |
| | | | | | | CURVE 42 | | CURVE 45 | | | |
| | | | | | | CURVE 43 | | CURVE 46 | | | |
| | | | | | | CURVE 44 | | CURVE 47 | | | |
| | | | | | | CURVE 45 | | CURVE 48 | | | |
| | | | | | | CURVE 46 | | CURVE 49 | | | |
| | | | | | | CURVE 47 | | CURVE 50 | | | |
| | | | | | | CURVE 48 | | CURVE 51 | | | |
| | | | | | | CURVE 49 | | CURVE 52 | | | |
| | | | | | | CURVE 50 | | CURVE 53 | | | |
| | | | | | | CURVE 51 | | CURVE 54 | | | |
| | | | | | | CURVE 52 | | CURVE 55 | | | |
| | | | | | | CURVE 53 | | CURVE 56 | | | |
| | | | | | | CURVE 54 | | CURVE 57 | | | |
| | | | | | | CURVE 55 | | CURVE 58 | | | |
| | | | | | | CURVE 56 | | CURVE 59 | | | |
| | | | | | | CURVE 57 | | CURVE 60 | | | |
| | | | | | | CURVE 58 | | CURVE 61 | | | |
| | | | | | | CURVE 59 | | CURVE 62 | | | |
| | | | | | | CURVE 60 | | CURVE 63 | | | |
| | | | | | | CURVE 61 | | CURVE 64 | | | |
| | | | | | | CURVE 62 | | CURVE 65 | | | |
| | | | | | | CURVE 63 | | CURVE 66 | | | |
| | | | | | | CURVE 64 | | CURVE 67 | | | |
| | | | | | | CURVE 65 | | CURVE 68 | | | |
| | | | | | | CURVE 66 | | CURVE 69 | | | |
| | | | | | | CURVE 67 | | CURVE 70 | | | |
| | | | | | | CURVE 68 | | CURVE 71 | | | |
| | | | | | | CURVE 69 | | CURVE 72 | | | |
| | | | | | | CURVE 70 | | CURVE 73 | | | |
| | | | | | | CURVE 71 | | CURVE 74 | | | |
| | | | | | | CURVE 72 | | CURVE 75 | | | |
| | | | | | | CURVE 73 | | CURVE 76 | | | |
| | | | | | | CURVE 74 | | CURVE 77 | | | |
| | | | | | | CURVE 75 | | CURVE 78 | | | |
| | | | | | | CURVE 76 | | CURVE 79 | | | |
| | | | | | | CURVE 77 | | CURVE 80 | | | |
| | | | | | | CURVE 78 | | CURVE 81 | | | |
| | | | | | | CURVE 79 | | CURVE 82 | | | |
| | | | | | | CURVE 80 | | CURVE 83 | | | |
| | | | | | | CURVE 81 | | CURVE 84 | | | |
| | | | | | | CURVE 82 | | CURVE 85 | | | |
| | | | | | | CURVE 83 | | CURVE 86 | | | |
| | | | | | | CURVE 84 | | CURVE 87 | | | |
| | | | | | | CURVE 85 | | CURVE 88 | | | |
| | | | | | | CURVE 86 | | CURVE 89 | | | |
| | | | | | | CURVE 87 | | CURVE 90 | | | |
| | | | | | | CURVE 88 | | CURVE 91 | | | |
| | | | | | | CURVE 89 | | CURVE 92 | | | |
| | | | | | | CURVE 90 | | CURVE 93 | | | |
| | | | | | | CURVE 91 | | CURVE 94 | | | |
| | | | | | | CURVE 92 | | CURVE 95 | | | |
| | | | | | | CURVE 93 | | CURVE 96 | | | |
| | | | | | | CURVE 94 | | CURVE 97 | | | |
| | | | | | | CURVE 95 | | CURVE 98 | | | |
| | | | | | | CURVE 96 | | CURVE 99 | | | |
| | | | | | | CURVE 97 | | CURVE 100 | | | |
| | | | | | | CURVE 98 | | CURVE 101 | | | |
| | | | | | | CURVE 99 | | CURVE 102 | | | |
| | | | | | | CURVE 100 | | CURVE 103 | | | |
| | | | | | | CURVE 101 | | CURVE 104 | | | |
| | | | | | | CURVE 102 | | CURVE 105 | | | |
| | | | | | | CURVE 103 | | CURVE 106 | | | |
| | | | | | | CURVE 104 | | CURVE 107 | | | |
| | | | | | | CURVE 105 | | CURVE 108 | | | |
| | | | | | | CURVE 106 | | CURVE 109 | | | |
| | | | | | | CURVE 107 | | CURVE 110 | | | |
| | | | | | | CURVE 108 | | CURVE 111 | | | |
| | | | | | | CURVE 109 | | CURVE 112 | | | |
| | | | | | | CURVE 110 | | CURVE 113 | | | |
| | | | | | | CURVE 111 | | CURVE 114 | | | |
| | | | | | | CURVE 112 | | CURVE 115 | | | |
| | | | | | | CURVE 113 | | CURVE 116 | | | |
| | | | | | | CURVE 114 | | CURVE 117 | | | |
| | | | | | | CURVE 115 | | CURVE 118 | | | |
| | | | | | | CURVE 116 | | CURVE 119 | | | |
| | | | | | | CURVE 117 | | CURVE 120 | | | |
| | | | | | | CURVE 118 | | CURVE 121 | | | |
| | | | | | | CURVE 119 | | CURVE 122 | | | |
| | | | | | | CURVE 120 | | CURVE 123 | | | |
| | | | | | | CURVE 121 | | CURVE 124 | | | |
| | | | | | | CURVE 122 | | CURVE 125 | | | |
| | | | | | | CURVE 123 | | CURVE 126 | | | |
| | | | | | | CURVE 124 | | CURVE 127 | | | |
| | | | | | | CURVE 125 | | CURVE 128 | | | |
| | | | | | | CURVE 126 | | CURVE 129 | | | |
| | | | | | | CURVE 127 | | CURVE 130 | | | |
| | | | | | | CURVE 128 | | CURVE 131 | | | |
| | | | | | | CURVE 129 | | CURVE 132 | | | |
| | | | | | | CURVE 130 | | CURVE 133 | | | |
| | | | | | | CURVE 131 | | CURVE 134 | | | |
| | | | | | | CURVE 132 | | CURVE 135 | | | |
| | | | | | | CURVE 133 | | CURVE 136 | | | |
| | | | | | | CURVE 134 | | CURVE 137 | | | |
| | | | | | | CURVE 135 | | CURVE 138 | | | |
| | | | | | | CURVE 136 | | CURVE 139 | | | |
| | | | | | | CURVE 137 | | CURVE 140 | | | |
| | | | | | | CURVE 138 | | CURVE 141 | | | |
| | | | | | | CURVE 139 | | CURVE 142 | | | |
| | | | | | | CURVE 140 | | CURVE 143 | | | |
| | | | | | | CURVE 141 | | CURVE 144 | | | |
| | | | | | | CURVE 142 | | CURVE 145 | | | |
| | | | | | | CURVE 143 | | CURVE 146 | | | |
| | | | | | | CURVE 144 | | CURVE 147 | | | |
| | | | | | | CURVE 145 | | CURVE 148 | | | |
| | | | | | | CURVE 146 | | CURVE 149 | | | |
| | | | | | | CURVE 147 | | CURVE 150 | | | |
| | | | | | | | | | | | |

TABLE 5. EXPERIMENTAL DATA ON THE ELECTRICAL RESISTIVITY OF BERYLLIUM Be (Temperature Dependence) (continued)

| T | ρ |
|----------|--------|
| CURVE 79 | |
| 303 | 4.8* |
| 350 | 6.8 |
| 390 | 15.5 |
| 617 | 26.3 |
| 661 | 30.0 |
| 730 | 32.9 |
| 751 | 34.1 |
| 891 | 33.7 |
| 943 | 32.9 |
| 1055 | 36.5 |
| 1163 | 34.6 |
| 1257 | 39.1 |
| 1274 | 42.8 |
| 1324 | 45.6 |
| 1409 | 47.0 |
| CURVE 80 | |
| 250 | 10.1 |
| 454 | 12.0 |
| 550 | 36.6 |
| 1165 | 36.0 |
| 1207 | 37.8 |
| 1255 | 41.7 |
| 1393 | 48.9 |
| 1454 | 53.8 |

* Not shown in figure.

4.2. Magnesium

Magnesium, with atomic number 12, is a silvery-white, light, and fairly tough metal. It has a close-packed hexagonal crystalline structure with a density of 1.74 g cm^{-3} at 293 K, which is 35% lighter than aluminum. It melts at 922 K and boils at about 1364 K. Its critical temperature has been estimated to be 3537 K. Naturally occurring magnesium is composed of three stable isotopes, the most abundant being ^{24}Mg , which constitutes 78.7%. Five other radioactive isotopes are known to exist. Magnesium is the seventh most abundant element in the continental crust of the earth (2.33% by weight).

Temperature Dependence

There are 59 sets of experimental data available for the electrical resistivity of magnesium. The information on specimen characterization and measurement condition for each of the data sets is given in Table 7. The data are tabulated in Table 8 and shown in Figures 4 and 5. Determinations of the electrical resistivity for both the solid and liquid phases cover continuously the temperature range from 1 to 1171 K.

Since monocrystalline magnesium is an anisotropic metal, resistivity values will vary with the direction of the resistivity measurements relative to the hexagonal axis of the crystal. Goens and Schmidt [35-37] (curves 46-59), Alderson and Hund [38] (curves 41 and 42), and Nichols [8] (curves 12-17) have made measurements on single crystals up to 473 K.

Only one data set is available for amorphous magnesium. Ferrier and Herrell [39] (curve 44) have measured the electrical resistivity of an amorphous specimen, which was produced by vapor quenching at liquid nitrogen temperature (curve 44). At 273 K the electrical resistivity of amorphous magnesium is about 4.5 times that of the polycrystalline material.

The resistivity minimum apparent in the results of Rorschack and Herlin [40] (curve 11), Spohr and Webber [41] (curves 19 and 20), and Sharkoff [42] (curves 38-40), can be attributed to an impurity effect caused by trace amounts of certain transition metals in solid solution [43].

Most earlier determinations of the electrical resistivity of polycrystalline magnesium resulted in higher resistivities than the recent ones. These results can be explained by the lower purity of the specimens. The present recommended values are based on the data of Roll and Motz [44] (curve 8), Delaplace et al. [45] (curves 23 and 24), Das and Gerritsen [46] (curve 29), Hedgcock and Muir [47] (curve 32), Seth and Wood [48] (curve

34), and Powell, Hickman and Tye [49] (curves 36 and 37). A least-mean-square-error fit to weighted values of $\rho - \rho_0$, uncorrected for thermal expansion of the material, was made with the modified Bloch-Grüneisen equation (8) from 20 to 900 K. Weights are assigned to individual data sets in such a way that they have approximately equal weight at the low and high temperature range. The following results were obtained for the coefficients in equation (8):

| S_1 | S_2 | S_3 | $(\theta_R)_0$ | C | P |
|---------------------------------------|---|--|----------------|-------|------|
| $6.83 \cdot 10^{-8} \Omega \text{ m}$ | $-0.302 \cdot 10^{-8} \Omega \text{ m}$ | $0.141 \cdot 10^{-8} \Omega \text{ m}$ | 426 K | 0.044 | 1.90 |

The Debye temperature deduced from the specific heat measurements is 396 ± 54 K, in rough agreement with our θ_R . Correction to the fitted values for thermal linear expansion yielded the final recommended values.

The recommended electrical resistivity values for single crystals of magnesium as measured along the c-axis are based on the data of Alderson and Hund [38] (curve 41), Toens and Schmidt [35] (curves 46-59), and Nichols [8] (curve 17). A least-mean-square-error fit to their data for $\rho - \rho_0$ was made with the modified Bloch-Grüneisen equation (8) from 15 to 472 K. The following values were found for the coefficients in equation (8):

| S_1 | S_2 | S_3 | $(\theta_R)_0$ | C | P |
|---------------------------------------|--|--|----------------|--------|------|
| $5.06 \cdot 10^{-8} \Omega \text{ m}$ | $0.670 \cdot 10^{-8} \Omega \text{ m}$ | $0.074 \cdot 10^{-8} \Omega \text{ m}$ | 363 K | -0.109 | 1.90 |

The resulting values were corrected for thermal linear expansion to get the final recommended values. The recommended values above 472 K are estimated.

The recommended electrical resistivity values for single crystals measured perpendicular to the c-axis are based on the data of Alderson and Hund [38] (curve 42), Goens and Schmidt [35] (curves 46-59), and Nichols [8] (curve 12). A least-mean-square-error fit to their data for $\rho - \rho_0$ was made with the modified Bloch-Grüneisen equation (8) from 15 to 469 K. The following values were found for the coefficients in equation (8):

| S_1 | S_2 | S_3 | $(\theta_R)_0$ | C | P |
|---------------------------------------|--|--|----------------|-------|------|
| $8.04 \cdot 10^{-8} \Omega \text{ m}$ | $-1.06 \cdot 10^{-8} \Omega \text{ m}$ | $0.349 \cdot 10^{-8} \Omega \text{ m}$ | 522 K | 0.202 | 1.90 |

The resulting values were corrected for thermal linear expansion to get the final recommended values. The recommended values above 469 K are estimated.

By using equation (7) and the above single crystal results, the resistivity values for the polycrystalline material can be calculated. The resulting calculated values are within $\pm 3\%$ of the recommended values obtained from the experimental data for polycrystal-

line specimens. This indicates that the grains in the polycrystalline specimens were essentially random in orientation.

There are three data sets available on the electrical resistivity of magnesium in the liquid state. Van Zytveld et al. [50] (curve 28) found a very small temperature dependence of the electrical resistivity. Scala and Robertson [51] (curve 43) found a weak negative temperature dependence, while Roll and Motz [44] (curve 8) found a positive temperature dependence. Comparison with the electrical resistivity data of other alkaline earth elements in the liquid state suggests that the electrical resistivity of liquid magnesium should have a weak negative temperature dependence. The data of Scala et al. have been normalized by matching their values with the data of Van Zytveld et al. at the melting point, 922 K. The normalized values from 922 to 1171 K were fitted with a linear equation to obtain:

$$\rho(T) = 26.1 - 0.0016 \times (T - 922) \quad 922 \text{ K} \leq T \leq 1200 \text{ K} \quad (12)$$

where ρ is in units of $10^{-8} \Omega \text{ m}$ and T in K. At the melting point (922 K), the electrical resistivity of magnesium in the liquid state is about 76% higher than that of the solid state.

The recommended values for the total and intrinsic electrical resistivities are listed in Table , and those for the total resistivity are also shown in Figures 4 and 5. The recommended values are corrected for the thermal expansion. The correction amounts to -0.48% at 1 K, -0.20% at 200 K, 0.57% at 500 K and 1.90% at 900 K. The recommended values for the total electrical resistivity are for 99.9+% magnesium and those below 100 K are applicable only to specimens with residual resistivities of $0.008 \cdot 10^{-8} \Omega \text{ m}$ (//to c-axis), $0.01 \cdot 10^{-8} \Omega \text{ m}$ (\perp to c-axis), and $0.0062 \cdot 10^{-8} \Omega \text{ m}$ (polycrystalline). The uncertainty in the recommended values for the total electrical resistivity is believed to be within $\pm 8\%$ below 30 K, $\pm 5\%$ from 30 to 100 K, $\pm 3\%$ from 100 to 600 K, $\pm 5\%$ from 600 to 922 K, and within $\pm 10\%$ above 922 K. Above 30 K the uncertainty in the recommended values for the intrinsic resistivity is slightly higher than that in the total electrical resistivity, because of possible deviations from the Matthiessen's Rule; below 30 K the values are very uncertain and are not listed in the table.

TABLE 6. RECOMMENDED ELECTRICAL RESISTIVITY OF MAGNESIUM
(Temperature Dependence)

[Temperature, T, K; Total Resistivity, ρ , $10^{-8} \Omega \text{m}$; Intrinsic Resistivity, ρ_i , $10^{-8} \Omega \text{m}$]

| T | Solid | | | | | |
|--------|--------------|----------|-------------|----------|-----------------|----------|
| | // to c-axis | | ⊥ to c-axis | | Polycrystalline | |
| | ρ | ρ_i | ρ | ρ_i | ρ | ρ_i |
| 1 | 0.0080* | | 0.0100* | | 0.0062* | |
| 4 | 0.0080* | | 0.0100* | | 0.0062* | |
| 7 | 0.0082* | | 0.0100* | | 0.0064* | |
| 10 | 0.0086* | | 0.0108* | | 0.0069* | |
| 15 | 0.0101* | | 0.0130* | | 0.0086* | |
| 20 | 0.0136* | | 0.0175* | | 0.0123* | |
| 25 | 0.0204* | | 0.0255* | | 0.0193* | |
| 30 | 0.0320 | 0.0240 | 0.0383 | 0.0283 | 0.0309 | 0.0247 |
| 35 | 0.0502 | 0.0422 | 0.0572 | 0.0472 | 0.0488 | 0.0426 |
| 40 | 0.0760 | 0.0680 | 0.0837 | 0.0737 | 0.0744 | 0.0682 |
| 45 | 0.110 | 0.102 | 0.119 | 0.109 | 0.109 | 0.102 |
| 50 | 0.151 | 0.143 | 0.164 | 0.154 | 0.151 | 0.145 |
| 60 | 0.255 | 0.247 | 0.282 | 0.272 | 0.261 | 0.255 |
| 70 | 0.381 | 0.373 | 0.430 | 0.420 | 0.398 | 0.392 |
| 80 | 0.520 | 0.512 | 0.603 | 0.593 | 0.557 | 0.551 |
| 90 | 0.671 | 0.663 | 0.789 | 0.778 | 0.728 | 0.722 |
| 100 | 0.827 | 0.819 | 0.983 | 0.973 | 0.908 | 0.902 |
| 110 | 0.986 | 0.978 | 1.18 | 1.17 | 1.10 | 1.09 |
| 120 | 1.15 | 1.14 | 1.38 | 1.37 | 1.28 | 1.27 |
| 130 | 1.31 | 1.30 | 1.58 | 1.57 | 1.47 | 1.46 |
| 140 | 1.47 | 1.46 | 1.77 | 1.76 | 1.66 | 1.65 |
| 150 | 1.63 | 1.62 | 1.96 | 1.95 | 1.84 | 1.83 |
| 175 | 2.02 | 2.01 | 2.44 | 2.43 | 2.30 | 2.29 |
| 200 | 2.42 | 2.41 | 2.90 | 2.89 | 2.75 | 2.74 |
| 225 | 2.81 | 2.80 | 3.35 | 3.34 | 3.19 | 3.18 |
| 250 | 3.19 | 3.18 | 3.80 | 3.79 | 3.61 | 3.60 |
| 273.15 | 3.54 | 3.53 | 4.20 | 4.19 | 4.05 | 4.04 |
| 293 | 3.84 | 3.83 | 4.55 | 4.54 | 4.39 | 4.38 |
| 300 | 3.94 | 3.93 | 4.67 | 4.66 | 4.51 | 4.50 |
| 350 | 4.68 | 4.67 | 5.52 | 5.51 | 5.36 | 5.35 |
| 400 | 5.42 | 5.41 | 6.39 | 6.38 | 6.19 | 6.18 |
| 450 | 6.16 | 6.15 | 7.25 | 7.24 | 7.03 | 7.02 |
| 500 | 6.90 | 6.89 | 8.09 | 8.08 | 7.86 | 7.85 |
| 550 | 7.53 | 7.52 | 8.93 | 8.92 | 8.69 | 8.68 |
| 600 | 8.35 | 8.34 | 9.76 | 9.75 | 9.52 | 9.51 |

* Provisional Values

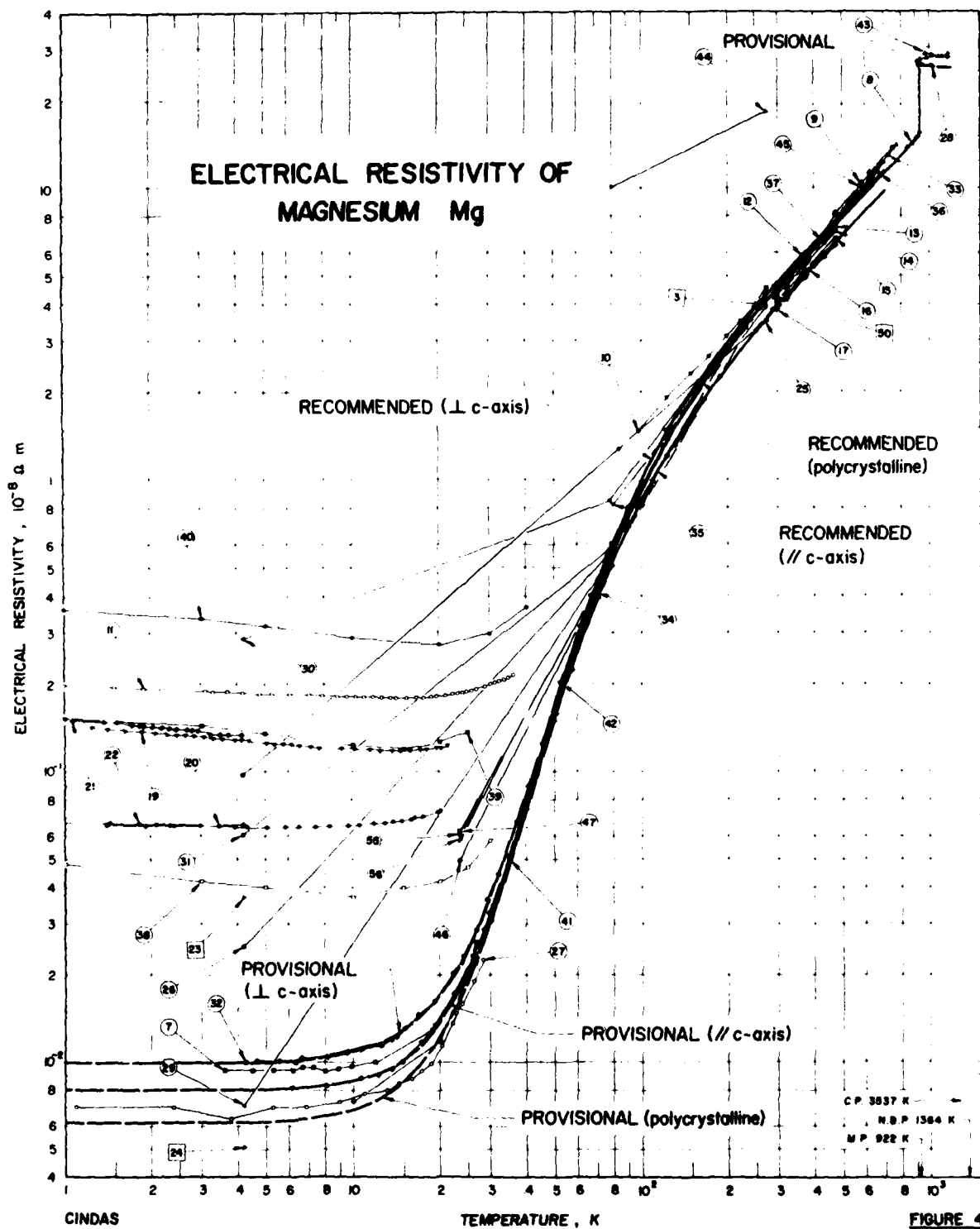
The recommended values for the total electrical resistivity are for 99.9% magnesium and those below 100 K are applicable only to specimens with residual resistivities of $0.008 \cdot 10^{-8} \Omega \text{m}$ (// to c-axis), $0.01 \cdot 10^{-8} \Omega \text{m}$ (⊥ to c-axis), and $0.0062 \cdot 10^{-8} \Omega \text{m}$ (polycrystalline).

TABLE6. RECOMMENDED ELECTRICAL RESISTIVITY OF MAGNESIUM (Continued)
(Temperature Dependence)

[Temperature, T, K; Total Resistivity, ρ , $10^{-8} \Omega m$; Intrinsic Resistivity, ρ_i , $10^{-8} \Omega m$]

| Solid | | | | | | | Liquid | |
|-------|--------------|----------|-------------------|----------|-----------------|----------|--------|--------|
| T | // to c-axis | | \perp to c-axis | | Polycrystalline | | T | ρ |
| | ρ | ρ_i | ρ | ρ_i | ρ | ρ_i | | |
| 650 | 9.07 | 9.06 | 10.6 | 10.6 | 10.4 | 10.4 | 922 | 26.1* |
| 700 | 9.78 | 9.77 | 11.4 | 11.4 | 11.2 | 11.2 | 950 | 26.1* |
| 750 | | | | | 12.0 | 12.0 | 1000 | 26.0* |
| 800 | | | | | 12.8 | 12.8 | 1050 | 25.9* |
| 850 | | | | | 13.6 | 13.6 | 1100 | 25.8* |
| 900 | | | | | 14.4 | 14.4 | 1150 | 25.7* |
| 922 | | | | | 14.7 | 14.7 | 1200 | 25.6* |

* Provisional Values.



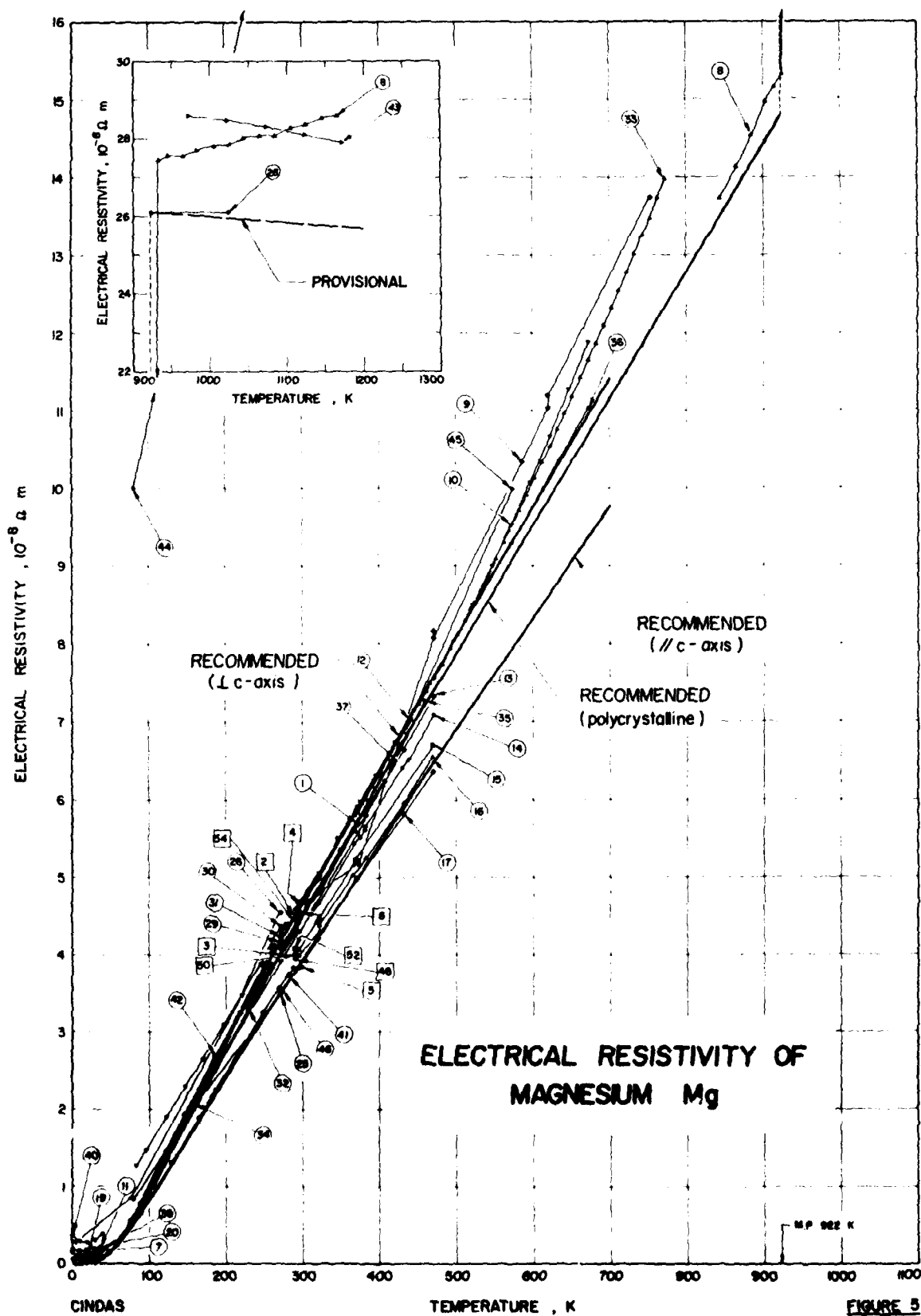


TABLE 7. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF MAGNESIUM Mg (Temperature Dependence)

| Cur. Ref. No. | Author(s) | Year | Method Used | Temp. Range, K | Name and Specimen Designation | Composition (weight percent), Specifications, and Remarks |
|---------------|--|------|-------------|----------------|-------------------------------|---|
| 1 52 | Lorenz, L. | 1881 | | 273-373 | Mg | Pure. |
| 2 53 | Das, K. B. and Gerritsen, A. N. | 1962 | | 293 | Mg | Spectrographically pure magnesium (Johnson-Matthey, Ltd., Lab. No. 4220); samples were alternately annealed at 400 C for 90 min; the samples varied in width from 0.15 to 0.311 cm, in thickness from 0.0037 to 0.0167 cm, and in length from 3.59 to 10.55 cm. |
| 3 54 | Vand, V. | 1943 | | 273 | Mg | Pure. |
| 4 55 | Baveja, K. D. | 1961 | in | 299 | Mg | Pure; the electrical resistivity was measured by magnetic damping method; unannealed specimen; diameter 0.2497 cm, thickness 0.0858 cm disc sample. |
| 5 33 | Kuczyński, G. C. | 1960 | | 300 | Mg \perp | Pure. |
| 6 33 | Kuczyński, G. C. | 1960 | | 300 | Mg \parallel | Pure. |
| 7 56 | Hedgcock, F. T., Muir, W. B. and Wallingford, E. | 1960 | | 3-26, 300 | Mg | <0.001 each Al, Fe, Mn, Pb, Si, Zn, <0.01 each Ca, Sn, <0.0005 Ni; the sample was made by Dow Chemical Co; the sample was annealed at 450 C for 48 hr in atm of helium gas. Reported error 1%. |
| 8 44 | Roll, A. and Metz, H. | 1957 | R | 844-1166 | | 99.8 pure; in solid and liquid states; M.P. 923 K; data corrected for thermal linear expansion. Reported error 1%. |
| 9 57 | Schofield, F. H. | 1924 | V | 293-753 | | 99.6 purity magnesium specimen was extruded to 0.75 in. diameter from a billet 5 in. in diameter; annealed at 360 C for 6 hr, and allowed to cool slowly; density at 294 K = 1.75 gm/cm ³ . Reported error 1%. |
| 10 58 | Nicolai, G. | 1908 | | 84-673 | | Pure. |
| 11 40 | Rorschach, H. E. and Herlin, M. A. | 1951 | | 1.5-36 | | Pure, bulk cylindrical sample; the resistivity was obtained by measuring the mutual inductance of two coaxial coils surrounding the sample. |
| 12 8 | Nichols, J. L. | 1955 | B | 273-497 | | 0.0036 C, 0.0005 Fe, 0.0002 Mn, 0.001 Ca, 0.0019 each K, Na, 0.0004 H ₂ , <0.01 Zn, <0.0005 Pb, <0.0001 each Al, Cu, Sr, B, <0.001 each Si, Sn, <0.0003 Ni; single crystal samples, 0.50 in. in diameter and 7 in. long, were grown in a gradient furnace; a Kelvin Double Bridge was used in conjunction with a high-sensitivity D'Arsonval type galvanometer for the resistance measurements; $\cos^2 \varphi = 0.002$, ϕ is the angle between sample's axis and c-axis. |
| 13 8 | Nichols, J. L. | 1955 | B | 273-497 | | Similar to the above specimen; $\cos^2 \varphi = 0.213$. |
| 14 8 | Nichols, J. L. | 1955 | B | 273-497 | | Similar to the above specimen; $\cos^2 \varphi = 0.430$. |
| 15 8 | Nichols, J. L. | 1955 | B | 273-497 | | Similar to the above specimen; $\cos^2 \varphi = 0.667$. |
| 16 8 | Nichols, J. L. | 1955 | B | 273-497 | | Similar to the above specimen; $\cos^2 \varphi = 0.841$. |
| 17 8 | Nichols, J. L. | 1955 | B | 273-497 | | Similar to the above specimen; $\cos^2 \varphi = 0.990$. |
| 18* 59 | Salkovitz, E. I., | 1957 | | 300 | | 99.98 pure, annealed extruded polycrystalline stripes; specimen width from 0.412 cm to 0.640 cm, thickness from 0.212 cm to 0.240 cm, and length from 9.54 cm to 29.3 cm; resistivity was obtained by using the Reeves modification of Kelvin double bridge. |
| 19 41 | Spohr, D. A. and Webber, R. T. | 1957 | | 1-25 | Mg (Fe) | 99.98% Mg, 0.013 Fe, 0.0023 Pb, 0.0023 Ni; cold-worked polycrystal from Johnson-Matthey and Co., London, England; the rod specimen was about 3.2 mm in diameter and 9 cm long. Reported error 0.3%. |

* Not shown in figure.

TABLE 7. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF MAGNESIUM Mg (Temperature Dependence) (continued)

| Cur. Ref. No. | Author(s) | Year | Method Used | Temp. Range, K | Name and Specimen Designation | Composition (weight percent), Specifications, and Remarks |
|---------------|---|------|-------------|----------------|-------------------------------|---|
| 20 | Spohr, D. A. and Webber, R. T. | 1957 | | 1-25 | Mg (Min) | 99.95% Mg, 0.043 Mn, 0.001 each Fe, Si, 0.0011 each Pb, Sn, 0.0002 Al, 0.0001 each Cu, Ni, 0.0016 Zn, 0.0012 Ca; annealed polycrystal rod, 3.2 mm in diameter and 9 cm long; prepared by Dow Chemical Co. Reported error 0.3%. |
| 21 | Hein, R. A. and Falge, R. L. | 1957 | | 0.3-4.3 | Mg (Fe) | 99.98% Mg, 0.013 Fe, 0.0023 Mn, 0.0013 Pb; cold-worked polycrystal rod 3.2 mm in diameter and 9 cm long; specimen was obtained from Johnson-Matthey and Co., England. |
| 22 | Hein, R. A. and Falge, R. L. | 1957 | | 0.3-4.3 | Mg (Mn) | 99.95% Mg, 0.043 Mn, 0.001 each Fe, Si, 0.0011 each Pb, Sn, 0.0002 Al, 0.0001 each Cu, Ni, 0.0016 Zn, 0.0012 Ca; annealed polycrystal rod 3.2 mm in diameter and 9 cm long; specimen was prepared by Dow Chemical Co. |
| 23 | Delaplace, J. | 1968 | | 4.2-300 | Mg 1 | 99.95 pure wire specimen; 0.2 mm in diameter; R _{300 K} /R _{4.2 K} = 120. |
| 24 | Delaplace, J. | 1968 | | 4.2-300 | Mg 2 | 99.999 pure zone refined wire specimen; 0.2 mm in diameter; R _{300 K} /R _{4.2 K} = 870. |
| 25 | Hedgcock, F. T. and Muir, W. B. | 1961 | | 4.2-273 | Mg | 0.04 Mn, R _{4.2/R273} = 0.023. |
| 26 | Bijvoet, J., de Iongh, B., Dekker, J. A., and Rathenau, G. W. | 1962 | | 4.2-273 | D Mg | Pure magnesium sample was supplied by Dow Chemical International. |
| 27 | Panova, G. Kh., Zhernov, A. P., and Kuznetsov, V. I. | 1968 | A | 1.2-20 | Mg | Pure magnesium wire sample 1 mm in diameter and 50 mm in length was prepared by drawing through a die and annealing subsequently in helium atm at 350 C. Reported error 1.2%. |
| 28 | Van Zytveld, J. B., Enderby, J. E., and Collings, E. W. | 1972 | A | 924, 1023 | Mg | 99.98 pure, <0.001 each Al, Si, Zn, <0.0005 each Cu, Pb, 0.003 Fe, 0.002 Mn, <0.0001 Ni, <0.003 each C, O, <0.003 H ₂ , 0.0015 N; sample was obtained from Koch Light Lab. Ltd. Reported error 4%. |
| 29 | Das, S. B. and Gerritsen, A. N. | 1964 | A | 4.2-273 | Mg | <0.01 Ca, <0.02 Zn, <0.0001 each Al, Cu, 0.001 Fe, 0.0011 Mn, <0.0002 Ni, 0.0005 Pb, <0.001 each Si, Sn; specimen was supplied by Dow Metal Products Co; polycrystalline specimen: R _{4.2/R273} = 1.7 x 10 ⁻³ . |
| 30 | Das, S. B. and Gerritsen, A. N. | 1964 | A | 4.2-273 | 0.16 Li | 0.16 Li, <0.001 each Al, Cu, Mn, Zn, <0.01 each Ca, Sn, <0.0005 Fe, 0.0009 Ni, <0.002 Pb, <0.003 Si; polycrystalline specimen was supplied by Dow Metal Products Co; R _{4.2/R273} = 0.0055. |
| 31 | Das, S. B. and Gerritsen, A. N. | 1964 | A | 4.2-273 | 0.047 Sn | 0.047 Sn, <0.001 each Al, Cu, Fe, Mn, <0.01 Ca, <0.0003 each Ni, Pb, <0.0001 Si, 0.003 Zn; polycrystalline specimen was supplied by Dow Metal Products Co; R _{4.2/R273} = 0.0144. |
| 32 | Hedgcock, F. T. and Muir, W. B. | 1964 | D | 4.27-571.2 | 728 | Pure; specimen was rolled into 0.01 in. strips, etched, cut into 0.125 x 4 in. and annealed in a helium atm at 7 cm of Hg at 450 C for 12 hr; R _{4.2/R273} = 2.467 x 10 ⁻³ . |
| 33 | Grube, G. and Burkhardt, A. | 1929 | B | 373-773 | | 99.93 Pure; 0.015 Si, 0.052 Fe, and trace of Al, Cu; the electrical resistivity was measured in 1 atm pressure of very pure hydrogen. |
| 34 | Seth, R. S. and Woods, S. B. | 1970 | | 10-295 | | <0.0014 impurity; obtained from Johnson Matthey, and Mallory, Ltd., Canada; prepared by Dow Chemical Co. from sublimed magnesium that was at least 99.98 pure after fabrication; slightly non-uniform 0.035 in. diameter wire drawn through 0.032 in. diamond die to produce uniform, smooth wire; annealed at 350 C for 8 hr in 10 torr H ₂ . |
| 35 | Saebler, J. | 1929 | | 80-460 | | Pure; 3 cm x 1.23 cm. |

TABLE 7. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF MAGNESIUM Mg (Temperature Dependence) (continued)

| Cur. Ref. No. | Author(s) | Year | Method Used | Temp. Range, K | Name and Specimen Designation | Composition (weight percent), Specifications, and Remarks |
|---------------|--|------|-------------|----------------|-------------------------------|---|
| 36 | Powell, R.W., Hickman, M.J., and Tye, R.P. | 1964 | | 293-673 | Mg 1 | 99.95 Mg, 0.033 Al, 0.012 Zn; 1.9 cm diameter x 30 cm long; supplied by the Metallurgy Division of the National Physical Laboratory; forged and heat treated. |
| 37 | Powell, R.W., et al. | 1964 | | 293-423 | Mg 2 | 99.98 Mg, 0.017 Al, 0.004 Zn; 0.635 cm diameter x 10 cm long; supplied by Messrs. Johnson, Matthey and Co., Ltd. |
| 38 | Sharkoff, E.G. | 1953 | | 1.0-30 | Sample No. 765 | 99.98 Mg, 0.01 Mn, 0.003 Zn, 0.0012 Pb, 0.001 Ca, <0.001 each Si, Sn, 0.008 Fe, 0.0002 Al, <0.0001 each Cu, Ni; 0.310 cm diameter x 9.03 cm long. |
| 39 | Sharkoff, E.G. | 1953 | | 1.0-25 | Sample No. 767 | 99.95 Mg, 0.043 Mn, 0.0043 Zn, 0.0012 Ca, 0.0011 each Pb, Sn, 0.0010 Fe, <0.001 Si, 0.0002 Al, <0.0001 each Cu, Ni; 0.307 cm diameter x 8.93 cm long. |
| 40 | Sharkoff, E.G. | 1953 | | 1.0-40 | Sample No. 370 | 99.87 Mg, 0.12 Mn, 0.0036 Zn, 0.0014 Pb, 0.0011 Fe, <0.001 each Si, Sn, 0.0006 Ca, 0.0002 Al, <0.0002 Ni, 0.0001 Cu; 0.305 cm diameter x 9.35 cm long. |
| 41 | Alderson, J.E.A. and Hurd, C.M. | 1975 | A | 3-300 | Mg 1, Mg 2 | 99.9 purity; single crystals; for Mg 1 specimen - 0.315 mm thick, probe separation 6.325 cm, angle between c-axis and sample's axis $\theta = 6.5^\circ$; for Mg 2 specimen - 0.253 mm thick, probe separation 5.36 cm, $\theta = 70.5^\circ$; $\rho_{\text{axis}}/\rho_{\text{area}} = 440$; longitudinal resistivity (ρ_L) data were obtained. |
| 42 | Alderson, J.E.A. and Hurd, C.M. | 1975 | A | 3-300 | Mg 1, Mg 2 | Same as the above specimen; transverse resistivity (ρ_T) data were obtained. |
| 43 | Scala, E. and Robertson, W.D. | 1953 | A | 973-1171 | | 99.975 Mg, 0.01 Cu, 0.004 Al, 0.003 Pb, and 0.003 Si; in liquid state; supplied by Dominion Magnesium, Ltd.; contained in a graphite tube about 0.6 cm I.D. and 13 cm long. |
| 44 | Ferrier, R.P. and Herrell, D.J. | 1970 | | 80-273 | | Pure; amorphous specimen was obtained by vapor quenching at liquid nitrogen temperature; data was extracted from the figure. |
| 45 | Heal, T.J. | 1958 | | 273-573 | | Pure; density 1.7398 g cm^{-3} ; melting point 923 K; boiling point 1353 K. |
| 46 | Goens, E. and Schmid, E. | 1936 | | 20.35-373.15 | Mg 50 | Pure; single crystal specimens were grown from the melt of 99.95 pure starting material; cylindrical specimen is about 4.53 cm in length and 0.1369 cm in radius; angle ϕ between sample axis and the hexagonal axis is 14.30° ; resistance ratio are reported, the resistivity are calculated from $\rho(291.15 \text{ K}) = 3.813 \cdot 10^{-8} \text{ Qm}$. |
| 47* | Goens, E. and Schmid, E. | 1936 | | 20.35-373.15 | XI | Similar to the above specimen except the specimen is about 14.56 cm in length, 0.2463 cm in radius; $\phi = 18.20^\circ$ and $\rho(291.15 \text{ K}) = 3.848 \cdot 10^{-8} \text{ Qm}$. |
| 48 | Goens, E. and Schmid, E. | 1936 | | 291.15 | XV | Similar to the above specimen except the specimen is about 11.39 cm in length, 0.2452 cm in radius; and $\phi = 29^\circ$. |
| 49* | Goens, E. and Schmid, E. | 1936 | | 291.15 | XIX | Similar to the above specimen except the specimen is about 9.193 cm in length and 0.1647 cm in radius; and $\phi = 34.30^\circ$. |
| 50 | Goens, E. and Schmid, E. | 1936 | | 291.15 | 90 | Similar to the above specimen except $\phi = 49^\circ$. |
| 51* | Goens, E. and Schmid, E. | 1936 | | 291.15 | XVI | Similar to the above specimen except the specimen is 6.304 cm in length, 0.16 cm in radius and $\phi = 52.45^\circ$. |

* Not shown in figure.

TABLE 7. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF MAGNESIUM Mg (Temperature Dependence) (continued)

| Cat. Ref. No. | Author(s) | Year | Method Used | Temp. Range, K | Name and Specimen Designation | Composition (weight percent), Specifications, and Remarks |
|---------------|--------------------------|------|-------------|----------------|-------------------------------|---|
| 53 | Goens, E. and Schmid, E. | 1936 | | 291.15 | 169 | Similar to the above specimen except the specimen is about 6.628 cm in length, 0.2002 cm in radius and $\varphi = 55^\circ 20'$. |
| 53* | Goens, E. and Schmid, E. | 1936 | | 291.15 | 94 | Similar to the above specimen except the specimen is about 10.36 cm in length, 0.1765 cm in radius and $\varphi = 63^\circ$. |
| 54 | Goens, E. and Schmid, E. | 1936 | | 291.15 | 85 | Similar to the above specimen except the specimen is about 8.486 cm in length, 0.1858 cm in radius and $\varphi = 73^\circ 50'$. |
| 55* | Goens, E. and Schmid, E. | 1936 | | 20.35-373.15 | 116 | Similar to the above specimen except the specimen is about 8.202 cm in length, 0.2053 cm in radius, $\varphi = 80^\circ$; resistance ratio at different temperatures were reported, the electrical resistivity data are calculated for $\rho(291.15 \text{ K}) = 4.492 \cdot 10^{-9} \Omega\text{m}$. |
| 56* | Goens, E. and Schmid, E. | 1936 | | 20.35-373.15 | 188 | Similar to the above specimen except $\varphi = 82^\circ$; the electrical resistivity data are calculated from resistance ratio data and $\rho(291.15 \text{ K}) = 4.516 \cdot 10^{-9} \Omega\text{m}$. |
| 57* | Goens, E. and Schmid, E. | 1936 | | 20.35-373.15 | 162 | Similar to the above specimen except the specimen is about 5.445 cm in length, 0.1919 cm in radius, the electrical resistivity data are calculated for resistance ratio data and $\rho(291.15 \text{ K}) = 4.492 \cdot 10^{-9} \Omega\text{m}$. |
| 58* | Goens, E. and Schmid, E. | 1931 | | 291.15 | ρ_{\perp} | Pure; single crystal specimen; specimen's axis perpendicular to the hexagonal axis; resistivity temperature coefficient $0.00416/\text{K}$ (273-373 K). |
| 59* | Goens, E. and Schmid, E. | 1931 | | 291.15 | ρ_{\parallel} | Pure; single crystal specimen; specimen's axis parallel to the hexagonal axis; resistivity temperature coefficient $0.00427/\text{K}$ (273-373 K). |

* Not shown in figure.

TABLE 8. EXPERIMENTAL DATA ON THE ELECTRICAL RESISTIVITY OF MAGNESIUM
[Temperature, T, K; Resistivity, ρ , 10^{-6} (cm)]

[illegible]

• Not shown in figure.

TABLE 8. EXPERIMENTAL DATA ON THE ELECTRICAL RESISTIVITY OF MAGNESIUM Mg (Temperature Dependence) (continued)

| CURVE 21 (cont.) | | | CURVE 26 | | | CURVE 32 | | | CURVE 33 (cont.) | | | CURVE 36 | | | CURVE 41 | | |
|------------------|---------|--|----------|--------|--|----------|--------|--|------------------|--------|--|----------|--------|--|----------|---------|--|
| T | ρ | | T | ρ | | T | ρ | | T | ρ | | T | ρ | | T | ρ | |
| 0.01 | 0.1094 | | 4.2 | 0.025 | | 4.27 | 0.010 | | 603 | 10.141 | | 293 | 4.5* | | 6.17 | 0.0022 | |
| 0.05 | 0.1391 | | 77 | 0.55 | | 6.24 | 0.010 | | 613 | 10.245 | | 323 | 5.01* | | 6.97 | 0.0022 | |
| 0.72 | 0.1397 | | 273 | 4.55 | | 14.15 | 0.012* | | 623 | 10.558 | | 373 | 5.85* | | 8.02 | 0.0053 | |
| 0.81 | 0.1399 | | | | | 20.10 | 0.016* | | 633 | 10.762 | | 473 | 7.57* | | 9.44 | 0.0056 | |
| 0.93 | 0.1370 | | | | | 24.76 | 0.022* | | 643 | 10.980 | | 573 | 9.30 | | 10.64 | 0.0055 | |
| 1.07 | 0.1310 | | | | | 34.86 | 0.031 | | 653 | 11.198 | | 673 | 11.04 | | 11.25 | 0.0059 | |
| 1.27 | 0.1493 | | | | | 41.32 | 0.035* | | 663 | 11.436 | | | | | 12.26 | 0.0091 | |
| 1.53 | 0.1494 | | 1.1 | 0.0070 | | 59.39 | 0.057 | | 673 | 11.661 | | | | | 12.88 | 0.0093 | |
| 1.73 | 0.1490 | | 2.4 | 0.0070 | | 79.9 | 0.050* | | 683 | 11.880 | | | | | 13.62 | 0.0093 | |
| 1.84 | 0.1456 | | 3.8 | 0.0064 | | 89.3 | 0.0720 | | 693 | 12.118 | | 293 | 4.34 | | 14.69 | 0.0098 | |
| 1.99 | 0.1447 | | 5.3 | 0.0070 | | 107.4 | 1.053* | | 703 | 12.347 | | 323 | 4.85 | | 14.86 | 0.0100 | |
| 2.04 | 0.1440 | | 6.9 | 0.0073 | | 124.3 | 1.371 | | 713 | 12.564 | | 373 | 5.70* | | 15.82 | 0.0111 | |
| 2.19 | 0.1429 | | 9.0 | 0.0078 | | 146.5 | 1.786* | | 723 | 12.803 | | 423 | 6.51 | | 17.10 | 0.0115 | |
| 2.22 | 0.1422 | | 11.0 | 0.0078 | | 177.1 | 2.342 | | 733 | 13.039 | | | | | 17.62 | 0.0123 | |
| 2.45 | 0.1413 | | 13.1 | 0.0080 | | 195.3 | 2.732 | | 743 | 13.262 | | | | | 19.23 | 0.0133 | |
| 2.55 | 0.1401 | | 14.4 | 0.0085 | | 230.5 | 3.310 | | 753 | 13.498 | | | | | 21.00 | 0.0134 | |
| 2.79 | 0.1400 | | 16.0 | 0.0084 | | 273.1 | 4.052* | | 763 | 13.751 | | | | | 24.16 | 0.0200 | |
| 2.92 | 0.1399 | | 17.3 | 0.0094 | | 292.2 | 4.368 | | 773 | 14.000 | | | | | 26.00 | 0.0222 | |
| 3.21 | 0.1393 | | 18.6 | 0.0099 | | 309.6 | 4.636* | | | | | | | | 27.04 | 0.0233 | |
| 3.26 | 0.1366* | | 20.3 | 0.0114 | | 329.8 | 4.990* | | | | | | | | 28.78 | 0.0256 | |
| 3.49 | 0.1359 | | 22.1 | 0.0136 | | 351.0 | 5.353 | | | | | | | | 29.52 | 0.0257 | |
| 3.52 | 0.1359* | | 22.8 | 0.0147 | | 371.2 | 5.693* | | | | | | | | 30.98 | 0.0379 | |
| 3.71 | 0.1352 | | 23.8 | 0.0159 | | | | | | | | | | | 31.34 | 0.0380* | |
| 4.15 | 0.1344 | | 26.2 | 0.0190 | | | | | | | | | | | 34.92 | 0.0498 | |
| | | | 28.2 | 0.0225 | | | | | | | | | | | 37.07 | 0.0604 | |
| | | | | | | | | | | | | | | | 38.38 | 0.0678* | |
| | | | | | | | | | | | | | | | 40.37 | 0.0808 | |
| | | | | | | | | | | | | | | | 42.57 | 0.0871* | |
| | | | | | | | | | | | | | | | 44.37 | 0.107 | |
| | | | | | | | | | | | | | | | 48.21 | 0.134 | |
| | | | | | | | | | | | | | | | 50.71 | 0.158 | |
| | | | | | | | | | | | | | | | 52.98 | 0.151 | |
| | | | | | | | | | | | | | | | 57.43 | 0.223 | |
| | | | | | | | | | | | | | | | 61.11 | 0.322 | |
| | | | | | | | | | | | | | | | 67.0 | 0.318* | |
| | | | | | | | | | | | | | | | 71.0 | 0.398 | |
| | | | | | | | | | | | | | | | 79.0 | 0.308 | |
| | | | | | | | | | | | | | | | 89.0 | 0.068 | |
| | | | | | | | | | | | | | | | 101 | 0.818 | |
| | | | | | | | | | | | | | | | 110 | 0.988 | |
| | | | | | | | | | | | | | | | 111 | 1.018 | |
| | | | | | | | | | | | | | | | 123 | 1.208 | |
| | | | | | | | | | | | | | | | 132 | 1.308 | |
| | | | | | | | | | | | | | | | 146 | 1.628* | |
| | | | | | | | | | | | | | | | 153 | 1.708* | |
| | | | | | | | | | | | | | | | 158 | 1.768* | |
| | | | | | | | | | | | | | | | 166 | 1.898 | |
| | | | | | | | | | | | | | | | 175 | 2.048 | |

* Not shown in figure.

TABLE 8. EXPERIMENTAL DATA ON THE ELECTRICAL RESISTIVITY OF MAGNESIUM Mg (Temperature Dependence) (continued)

| T | ρ | T | ρ | T | ρ | T | ρ |
|------------------|---------|------------------|--------|-----------|---------|-------------------|--------|
| CURVE 41 (cont.) | | CURVE 42 (cont.) | | CURVE 46 | | CURVE 55 (cont.)* | |
| 154 | 2.323 | 50.83 | 0.174* | 20.35 | 0.0492* | 90.05 | 0.795 |
| 224 | 2.826* | 52.62 | 0.202 | 77.90 | 0.505 | 273.15 | 4.179 |
| 250 | 3.244 | 57.16 | 0.249* | 90.05 | 0.686* | 291.15 | 4.492 |
| 263 | 3.439* | 61.53 | 0.314 | 273.15 | 3.543 | 373.15 | 5.916 |
| 271 | 3.568 | 63.0 | 0.34* | 291.15 | 3.813* | CURVE 56* | |
| 283 | 3.708* | 67.0 | 0.40 | 373.15 | 5.044* | 20.35 | 0.0379 |
| 283 | 3.719 | 72.0 | 0.47* | CURVE 47* | | 77.90 | 0.582 |
| 299 | 3.938 | 79.0 | 0.60 | 20.35 | 0.062 | 90.05 | 0.797 |
| CURVE 42 | | 89.0 | 0.79 | 77.90 | 0.503 | 273.15 | 4.201 |
| 4.65 | 0.0101 | 101 | 0.98 | 90.05 | 0.685 | 291.15 | 4.516 |
| 4.56 | 0.0101* | 109 | 1.20* | 273.15 | 3.576 | 373.15 | 5.948 |
| 5.22 | 0.0101* | 123 | 1.47 | 291.15 | 3.848 | CURVE 57* | |
| 5.35 | 0.0101 | 132 | 1.56* | 373.15 | 5.087 | 20.35 | 0.0573 |
| 6.00 | 0.0102* | 147 | 1.93 | CURVE 48 | | 77.90 | 0.579 |
| 6.41 | 0.0103 | 153 | 2.03* | 291.15 | 3.957 | 90.05 | 0.793 |
| 7.26 | 0.0103* | 157 | 2.11* | CURVE 49* | | 273.15 | 4.179 |
| 9.11 | 0.0105 | 166 | 2.26 | 291.15 | 4.218 | 291.15 | 4.492 |
| 9.55 | 0.0108 | 175 | 2.45* | CURVE 50 | | 373.15 | 5.917 |
| 10.72 | 0.0111 | 188 | 2.69 | 291.15 | 4.263 | CURVE 58* | |
| 11.22 | 0.0113* | 225 | 3.38* | CURVE 51* | | 291.15 | 4.54 |
| 12.20 | 0.0115 | 250 | 3.85 | 291.15 | 4.373 | CURVE 59* | |
| 12.93 | 0.0119 | 263 | 4.08 | CURVE 52 | | 291.15 | 3.77 |
| 13.52 | 0.0121 | 272 | 4.24* | 291.15 | 4.468 | CURVE 55* | |
| 14.02 | 0.0123 | 280 | 4.40 | CURVE 53* | | 20.35 | 0.0602 |
| 14.79 | 0.0126* | 284 | 4.44* | 291.15 | 4.408 | 77.90 | 0.582 |
| 15.07 | 0.0131 | 289 | 4.56* | CURVE 54 | | CURVE 55* | |
| CURVE 43 | | CURVE 44 | | CURVE 45 | | CURVE 55* | |
| 15.85 | 0.0138* | 973 | 28.6 | 273.15 | 3.90* | CURVE 55* | |
| 16.55 | 0.0146 | 1023 | 28.5 | 373.15 | 5.54* | CURVE 55* | |
| 17.79 | 0.0152* | 1074 | 24.3* | 573.15 | 10.00 | CURVE 55* | |
| 19.15 | 0.0163 | 1124 | 24.1 | CURVE 45 | | CURVE 55* | |
| 20.70 | 0.0181* | 1171 | 27.9 | 273.15 | 3.90* | CURVE 55* | |
| 22.24 | 0.0201 | CURVE 44 | | 373.15 | 5.54* | CURVE 55* | |
| 24.10 | 0.0222 | CURVE 45 | | 573.15 | 10.00 | CURVE 55* | |
| 25.49 | 0.0244* | CURVE 46 | | CURVE 46 | | CURVE 55* | |
| 26.86 | 0.0265 | CURVE 47 | | CURVE 47 | | CURVE 55* | |
| 28.74 | 0.0310* | CURVE 48 | | CURVE 48 | | CURVE 55* | |
| 29.65 | 0.0363 | CURVE 49 | | CURVE 49 | | CURVE 55* | |
| 31.44 | 0.0430* | CURVE 50 | | CURVE 50 | | CURVE 55* | |
| 31.70 | 0.0444 | CURVE 51 | | CURVE 51 | | CURVE 55* | |
| 34.36 | 0.0531* | CURVE 52 | | CURVE 52 | | CURVE 55* | |
| 37.67 | 0.0672 | CURVE 53 | | CURVE 53 | | CURVE 55* | |
| 38.92 | 0.0749 | CURVE 54 | | CURVE 54 | | CURVE 55* | |
| 40.56 | 0.0883 | CURVE 55 | | CURVE 55 | | CURVE 55* | |
| 42.04 | 0.0947* | CURVE 56 | | CURVE 56 | | CURVE 55* | |
| 45.00 | 0.124 | CURVE 57 | | CURVE 57 | | CURVE 55* | |
| 48.50 | 0.144* | CURVE 58 | | CURVE 58 | | CURVE 55* | |

* Not shown in figure.

4.3. Calcium

Calcium, with atomic number 20, is a silvery-white moderately soft metal. It has a face-centered cubic crystalline structure, which transforms to body-centered cubic form around 720 K. Its density is 1.55 gm cm^{-3} at 293 K. It melts at 113 K and boils at 1795 K. Impure calcium can also occur in a close-packed hexagonal form, which is stabilized by the impurities in calcium and is stable between about 523 and 720 K. Naturally occurring calcium is composed of six stable isotopes, the most abundant being ^{40}Ca which constitutes 96.97%. Eight other radioactive isotopes are known to exist. Calcium is the fifth most abundant element in the earth's continental crust, of which it forms 4.15% by weight.

Temperature Dependence

There are 16 sets of experimental data available for the electrical resistivity of calcium. The information on specimen characterization and measurement condition for each of the data sets is given in Table 10. The data are tabulated in Table 11 and shown in Figures 6 and 7. Determinations of the electrical resistivity for both the solid and liquid states cover continuously the temperature range from 1.36 to 1138 K.

The data for the electrical resistivity of calcium show considerable scatter. Around room temperature, there is a sudden jump from the low-temperature data to those above room temperature as if there is a phase transition. This discrepancy is probably due to specimen contamination at higher temperatures. Katerberg et al. [68] (curve 10) found a small discontinuity near the phase transition temperature around 720 K. The data of Smith et al. [69] (curves 4 and 5) also show slope changes near the transition, which, however, give a quite different shape from that indicated by the data of Katerberg. The data of Swischer [70] (curves 14-16) do not show any discontinuities. The recommended values were generated based on the data of Cook and Laubitz [71] (curve 12) and Kayser and Soderquist [72] (curve 1). A least-mean-square-error fit was made with the modified Bloch-Grüneisen equation (8) to the selected data for $\rho - \rho_0$ from 30 to 300 K and to the estimated values up to 1113 K. At the phase transition temperature around 720 K the possible discontinuity was ignored. The following results were obtained for the coefficients in equation (8):

| S_1 | S_2 | S_3 | $(\theta_R)_0$ | C | P |
|---|---|---|----------------|--------|-----|
| $3.341 \cdot 10^{-8} \Omega \cdot \text{m}$ | $0.296 \cdot 10^{-8} \Omega \cdot \text{m}$ | $0.087 \cdot 10^{-8} \Omega \cdot \text{m}$ | 300.9 K | 0.0281 | 2.0 |

The Debye temperature deduced from specific heat measurements is $234 \pm 5 \text{ K}$ which is

about 20% lower than the present value for θ_R . The resulting values from equation (8) were then corrected for thermal linear expansion to become the final recommended values.

Only one data set is available on the electrical resistivity of calcium in the liquid state. Van Zytveld et al. [50] (curve 6) found that the temperature dependence of electrical resistivity is small and weakly negative. At the melting point (1113 K), the electrical resistivity of calcium in the liquid state is about 126% higher than that of solid calcium.

The recommended values for the total and intrinsic electrical resistivities are listed in Table 9, and those for the total resistivity are also shown in Figures 6 and 7. The recommended values for the total electrical resistivity are for 99.96% calcium and those below 30 K are applicable only to a specimen with residual resistivity of $0.045 \cdot 10^{-8} \Omega \text{ m}$. The recommended values from 1 to 293 K are corrected for the thermal linear expansion. The correction amounts to -0.47% at 1 K, -0.38% at 100 K and -0.2% at 200 K. The uncertainty in the recommended values for the total electrical resistivity is believed to be within $\pm 10\%$ below 40 K, within $\pm 5\%$ from 40 to 300 K, and within $\pm 20\%$ from 300 to 1150 K. Above 40 K the uncertainty in the recommended values for the intrinsic resistivity is slightly higher than that in the total electrical resistivity because of the possible deviations from the Matthiessen's Rule; below 40 K the ρ_i values are very uncertain and are not listed in the table.

TABLE 9. RECOMMENDED ELECTRICAL RESISTIVITY OF CALCIUM
(Temperature Dependence)

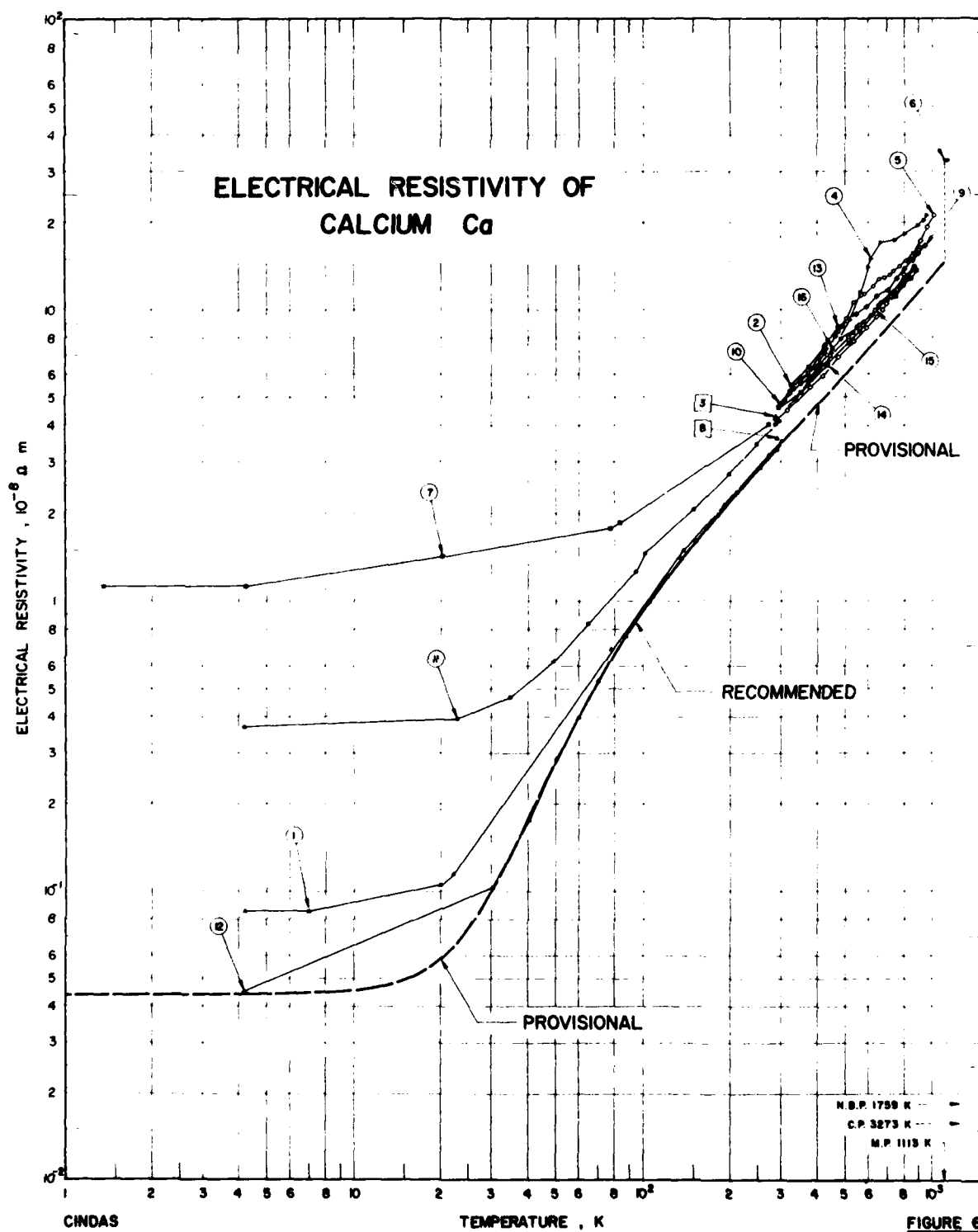
[Temperature, T, K; Total Resistivity, ρ , $10^{-8} \Omega \text{ m}$; Intrinsic Resistivity, ρ_i , $10^{-8} \Omega \text{ m}$]

| Solid | | | | | |
|-------|--------|----------|--------|--------|----------|
| T | ρ | ρ_i | T | ρ | ρ_i |
| 1 | 0.045* | | 250 | 2.82 | 2.77 |
| 4 | 0.045* | | 273.15 | 3.11 | 3.06 |
| 7 | 0.046* | | 293 | 3.36 | 3.31 |
| 10 | 0.047* | | 300 | 3.45 | 3.40 |
| 15 | 0.051* | | 350 | 4.09* | 4.04* |
| 20 | 0.060* | | 400 | 4.73* | 4.68* |
| 25 | 0.075* | | 450 | 5.37* | 5.32* |
| 30 | 0.100* | | 500 | 6.02* | 5.97* |
| 35 | 0.133* | | 550 | 6.68* | 6.63* |
| 40 | 0.175 | 0.130 | 600 | 7.35* | 7.30* |
| 45 | 0.224 | 0.179 | 650 | 8.02* | 7.97* |
| 50 | 0.277 | 0.232 | 700 | 8.70* | 8.65* |
| 60 | 0.396 | 0.351 | 750 | 9.38* | 9.33* |
| 70 | 0.522 | 0.477 | 800 | 10.0 * | 10.0 * |
| 80 | 0.652 | 0.607 | 850 | 10.7 * | 10.7 * |
| 90 | 0.782 | 0.737 | 900 | 11.4 * | 11.4 * |
| 100 | 0.913 | 0.868 | 950 | 12.1 * | 12.1 * |
| 110 | 1.04 | 0.997 | 1000 | 12.8 * | 12.8 * |
| 120 | 1.17 | 1.12 | 1100 | 14.3 * | 14.3 * |
| 130 | 1.30 | 1.25 | 1113 | 14.5 * | 14.5 * |
| 140 | 1.43 | 1.38 | | | |
| 150 | 1.56 | 1.51 | | | |
| 175 | 1.88 | 1.83 | | | |
| 200 | 2.19 | 2.14 | | | |
| 225 | 2.51 | 2.46 | | | |

| Liquid | |
|--------|--------|
| T | ρ |
| 1113 | 33.0* |
| 1150 | 33.0* |

* Provisional values.

The recommended values for the total electrical resistivity are for 99.96+% pure calcium and those at temperatures below 30 K are applicable only to a specimen with residual resistivity of $0.045 \times 10^{-8} \Omega \text{ m}$.



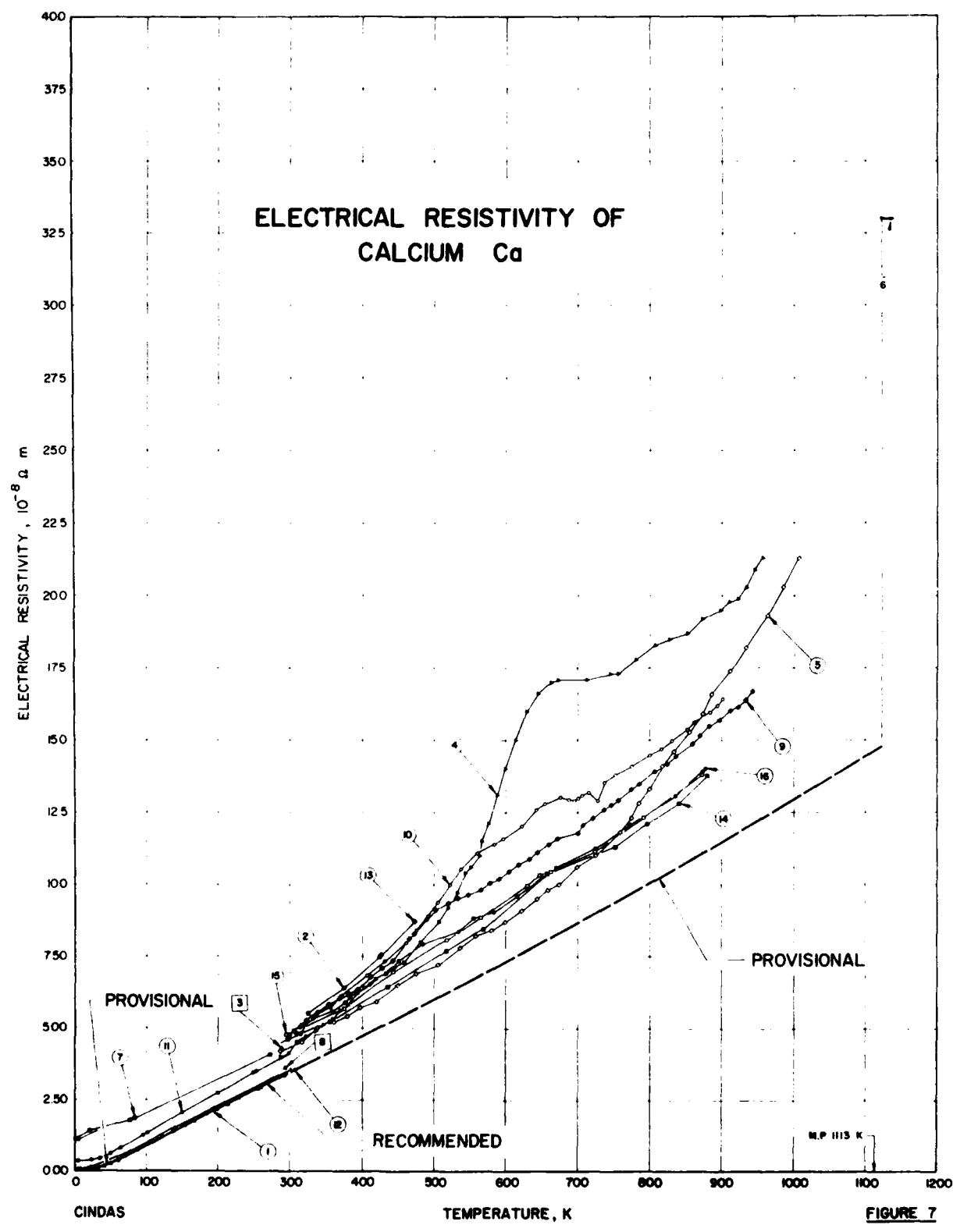


FIGURE 7

TABLE 10. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF CALCIUM Ca (Temperature Dependence)

| Cur. Ref. No. | Author(s) | Year | Method Used | Temp. Range, K | Name and Specimen Designation | Composition (weight percent), Specifications, and Remarks |
|---------------|---|------|-------------|----------------|-------------------------------|--|
| 1 72 | Kayser, F.Y. and Soderquist, S.D. | 1967 | | 4.2-300 | Ca | 99.96 Ca, 0.025 Sr, 0.005 O, 0.003 H, 0.0015 Mg, 0.0011 Ni, 0.0025 In. diameter wire specimens; annealed for 2 hr at 525 K under 8×10^{-4} torr; $\rho_{273.2 K} = 3.16 \mu\Omega$ cm. reported error $\pm 2\%$. |
| 2 73 | Cock, J.G. and Van der Meer, M.P. | 1973 | | 325-425 | Ca | 99+ purity, smoothed values extracted from table, data uncorrected for thermal expansion; resistance ratio 3. |
| 3 74 | Rineck, E. | 1931 | | 289 | Ca | Pure calcium was prepared by diffusion technique, 1.245 cm in diameter and 10 cm long cylindrical sample. |
| 4 69 | Smith, J.F., Carlson, D.N., and Vest, R.W. | 1956 | B | 273-973 | Ca A | 99.66 Ca, 0.3 Mg, 0.025 N, 0.006 Fe, 0.001 Al, 0.004 Mn; sample was heated at 600 C for 8 hr after four successive distillations at 900 C; 0.2 in. in diameter and 5 in. long. |
| 5 69 | Smith, J.F., et al. | 1956 | B | 273-973 | Ca C | 99.96 Ca, 0.01 Mg, 0.011 N, 0.010 Fe, 0.001 Al, 0.005 Ni; 0.2 in. in diameter and 5 in. long. |
| 6 50 | Van Zytveld, J.B., Enderby, J.E., and Collings, E.M. | 1972 | | 1123-1138 | | 99.9 pure, 0.001 each Al, Fe, 0.02 N, 0.001-0.002 each Co, In, B, 0.001-0.02 Li, 0.01-0.05 Mg; sample was obtained from Atomergic Chemicals Co. |
| 7 27 | Melander, W. and Voigt, B. | 1930 | - | 1.36-273.16 | Ca 1 | Pure; specimen was enclosed in a glass tube filled with helium gas; specimen dimension $1.2 \times 1.2 \times 59$ mm; electrical resistance was measured by compensation method with a mirror galvanometer; no thermal expansion correction for electrical resistivity data. |
| 8 75 | Frank, V. and Jeppesen, O.G. | 1953 | | 293.15 | Ca | 99+ Ca; 0.203 ± 0.002 mm thickness, 17 mm width, 48 mm long; density = 1.543 ± 0.004 g cm $^{-3}$, lattice constant = $5.59 \pm 0.01 \times 10^{-8}$ cm (face-centered cubic). |
| 9 68 | Katerberg, J., Niemeyer, S., Penning, D., and Van Zytveld, J.B. | 1975 | A | 308-944 | | 99.5 pure, major metallic impurities were other alkaline earth metals; specimen was supplied by Atomergic Chemicals Co.; the sample was mounted on stainless steel and high purity alumina with their surfaces exposed to the dynamic vacuum; measurements were taken with sample held under an atmosphere pressure of pure inert gas; data was extracted from figure. |
| 10 68 | Katerberg, J., et al. | 1975 | A | 300-902 | | Similar to the above specimen except it was supplied by Hall Co.; data was extracted from the graph. |
| 11 71 | Cock, J.G., Laubitz, M.J., and Van der Meer, M.P. | 1975 | A | 4.2-299.3 | Ca 2 | High purity (99% pure) Ca was sublimed at 1100 K in an Ar atmosphere of 6 mm Hg onto a 304 stainless steel plate kept near 570 K; cylindrical sample was cast from the purified by filling 1.2 cm diameter tubes with dendrites, welding caps onto their ends, heating them above the melting points of Ca in a vacuum furnace and then slowly cooling them; the resistance ratio near 10. |
| 12 71 | Cock, J.G., et al. | 1975 | D | 4.2-306.27 | Ca 3 | Similar to the above specimen; except Ta tubing and caps were used; the resistance ratio was near 70. |
| 13 71 | Cock, J.G., et al. | 1975 | A | 324.09-4731 | Ca 1 | 99% pure commercial calcium. |
| 14 70 | Swisher, C.L. | 1917 | B | 297-569 | O | 99.37 pure; specimen was obtained from Kallibaum; wire specimen 0.23 cm in diameter and 10.4 cm in length; measurements were taken in vacuum. |
| 15 70 | Swisher, C.L. | 1917 | B | 295-631 | P | Similar to the above specimen; except 0.27 cm in diameter and 10.0 cm in length. |

TABLE 10. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF CALCIUM Ca (Temperature Dependence) (Continued)

| Cur. Ref. No. | Author(s) | Year | Method Used | Temp. Range, K | Name and Specimen Designation | Composition (weight percent), Specifications, and Remarks |
|------------------|---------------|------|----------------|-------------------|-------------------------------------|--|
| 16 70 | Swisher, C.L. | 1917 | B | 295-535 | Q | Similar to the above specimen; except 0.275 cm in diameter and 7.5 cm in length. |

| T | ρ | T | ρ | T | ρ | T | ρ | T | ρ |
|-----------------|--------|-----------------|-----------------|-----------------|--------|-----------------|--------|-----|--------|
| <u>CURVE 1</u> | | | | | | | | | |
| 4.2 | 0.0-5 | 5-9 | 13.1 | 800 | 13.3 | 520 | 9.34* | 538 | 10.54 |
| 7.1 | 0.0-5 | 600 | 14.0 | 818 | 14.1 | 534 | 9.53* | 561 | 11.09* |
| 19.5 | 0.105 | 614 | 15.0 | 824 | 14.6 | 548 | 9.65 | 585 | 11.38 |
| 22.2 | 0.115 | 630 | 16.0 | 856 | 15.3 | 565 | 9.80* | 597 | 11.56* |
| 77.4 | 0.635 | 646 | 16.6 | 874 | 15.9 | 579 | 10.03* | 623 | 12.01 |
| 139.7 | 1.50 | 664 | 17.0 | 886 | 16.6 | 591 | 10.20 | 642 | 12.56* |
| 191.0 | 2.14 | 674 | 17.1 | 913 | 17.4 | 604 | 10.44* | 654 | 12.77 |
| 194.9 | 2.20 | 714 | 17.1 | 934 | 18.2 | 617 | 10.67* | 676 | 13.01* |
| 272.5 | 3.17 | 746 | 17.3 | 964 | 19.3 | 633 | 10.83* | 696 | 12.90* |
| 361.1 | 3.53 | 758 | 17.3 | 986 | 20.3 | 645 | 11.11 | 696 | 12.90* |
| <u>CURVE 2</u> | | | | | | | | | |
| 808 | 18.3 | 762 | 17.8 | 1007 | 21.3 | 660 | 11.38* | 701 | 12.98* |
| 828 | 18.5 | <u>CURVE 6</u> | | | | | | | |
| 853 | 18.7 | 4.22 | 1.131 | 701 | 11.75 | 716 | 13.16 | 707 | 13.07* |
| 874 | 19.2 | 20.45 | 1.432 | 708 | 12.02* | 728 | 12.87* | 718 | 13.16 |
| 899 | 19.5 | 77.59 | 1.781 | 721 | 12.27* | 738 | 13.53 | 728 | 12.87* |
| 911 | 19.8 | 83.97 | 1.856 | 737 | 12.57* | 753 | 13.79* | 738 | 13.53 |
| 923 | 19.9 | 273.16 | 4.050 | 747 | 12.75* | 775 | 14.08 | 753 | 13.79* |
| 934 | 20.3 | <u>CURVE 7</u> | | | | | | | |
| 946 | 20.9 | 1.26 | 1.131 | 766 | 13.47* | 831 | 14.97* | 775 | 14.08 |
| 958 | 21.3 | 4.22 | 1.137 | 807 | 13.85 | 853 | 15.35* | 831 | 14.97* |
| <u>CURVE 3</u> | | | | | | | | | |
| 289 | 4.3 | 20.45 | 1.432 | 824 | 14.15* | 863 | 15.60 | 853 | 15.35* |
| <u>CURVE 4</u> | | | | | | | | | |
| 287 | 4.0 | 77.59 | 1.781 | 837 | 14.43* | 884 | 15.95* | 863 | 15.60 |
| 299 | 4.1 | 83.97 | 1.856 | 860 | 14.65 | 894 | 15.46* | 884 | 15.95* |
| 310 | 4.5 | 273.16 | 4.050 | 871 | 15.16* | 894 | 15.46* | 894 | 15.46* |
| 322 | 4.7 | <u>CURVE 8</u> | | | | | | | |
| 325 | 4.9 | 293.15 | 3.60 \pm 0.03 | 898 | 15.70 | 913 | 16.01* | 894 | 15.46* |
| 346 | 5.1 | <u>CURVE 9</u> | | | | | | | |
| 359 | 5.3 | 308 | 4.83 | 913 | 16.01* | 924 | 16.15* | 913 | 16.01* |
| 370 | 5.6 | 315 | 4.78* | 934 | 16.39* | 944 | 16.66 | 924 | 16.15* |
| 391 | 5.8 | 323 | 5.26 | 944 | 16.66 | <u>CURVE 10</u> | | | |
| 395 | 6.2 | 328 | 5.53* | 4.2 0.369 | | | | | |
| 404 | 6.4 | 334 | 5.80 | 23.0 0.393 | | | | | |
| 419 | 6.7 | 339 | 6.03* | 35.0 0.468 | | | | | |
| 433 | 6.9 | 369 | 6.19* | 49.6 0.622 | | | | | |
| 415 | 7.1 | 382 | 6.34 | 64.6 0.833 | | | | | |
| 429 | 7.3 | 395 | 6.76* | 84.6 0.833 | | | | | |
| 432 | 8.0 | 412 | 7.08 | 101.46 1.261 | | | | | |
| 4507 | 8.7 | 428 | 7.31* | 153.68 2.069 | | | | | |
| 639 | 9.2 | 443 | 7.53* | 200.01 2.734 | | | | | |
| 675 | 9.7 | 466 | 8.10 | 200.42 2.758* | | | | | |
| 699 | 10.4 | 474 | 8.29* | 249.70 3.442 | | | | | |
| 728 | 10.6 | 490 | 8.80 | 253.62 3.493 | | | | | |
| 756 | 11.0 | 503 | 9.11* | 299.3 4.139* | | | | | |
| 775 | 11.5 | <u>CURVE 11</u> | | | | | | | |
| 785 | 12.1 | 4.2 0.369 | | | | | | | |
| <u>CURVE 12</u> | | | | | | | | | |
| 293 | 4.76 | 4.2 | 0.045 | 23.0 | 0.393 | 49.6 | 0.622 | 297 | 4.6 |
| 375 | 5.66 | 30.43 | 0.1037 | 35.0 | 0.468 | 64.6 | 0.833 | 356 | 5.2 |
| 443 | 6.97 | 40.34 | 0.1777 | 49.6 | 0.622 | 84.6 | 0.833 | 437 | 6.44 |
| 518 | 8.07 | 46.34 | 0.1777 | 101.46 | 1.261 | 94.59 | 1.261 | 517 | 7.68 |
| | | | | 153.68 | 2.069 | 101.46 | 1.261 | 569 | 8.44 |
| | | | | 200.01 | 2.734 | 153.68 | 2.069 | 657 | 10.36 |
| | | | | 200.42 | 2.758* | 200.01 | 2.734 | 733 | 11.28 |
| | | | | 249.70 | 3.442 | 200.42 | 2.758* | 797 | 12.08 |
| | | | | 253.62 | 3.493 | 249.70 | 3.442 | 841 | 12.60 |
| | | | | 299.3 | 4.139* | 253.62 | 3.493 | 881 | 13.76 |
| | | | | | | 299.3 | 4.139* | | |
| | | | | <u>CURVE 13</u> | | | | | |
| | | | | 324.49 | 5.501* | | | 293 | 4.76 |
| | | | | 373.87 | 6.378* | | | 375 | 5.66 |
| | | | | 457.5 | 7.321 | | | 443 | 6.97 |
| | | | | 473.1 | 8.720 | | | 518 | 8.07 |
| | | | | <u>CURVE 14</u> | | | | | |
| | | | | 297 | 4.6 | | | | |
| | | | | 356 | 5.2 | | | | |
| | | | | 437 | 6.44 | | | | |
| | | | | 517 | 7.68 | | | | |
| | | | | 569 | 8.44 | | | | |
| | | | | 657 | 10.36 | | | | |
| | | | | 733 | 11.28 | | | | |
| | | | | 797 | 12.08 | | | | |
| | | | | 841 | 12.60 | | | | |
| | | | | 881 | 13.76 | | | | |
| | | | | <u>CURVE 15</u> | | | | | |
| | | | | 293 | 4.76 | | | | |
| | | | | 375 | 5.66 | | | | |
| | | | | 443 | 6.97 | | | | |
| | | | | 518 | 8.07 | | | | |

Not shown in figure.

TABLE 11. EXPERIMENTAL DATA ON THE ELECTRICAL RESISTIVITY OF CALCIUM Ca (Temperature Dependence) (Continued)
 [Temperature, T, K; Resistivity, ρ , $10^{-8} \Omega\text{m}$]

| T | ρ |
|------------------|--------|
| CURVE 13 (cont.) | |
| 565 | 9.55 |
| 631 | 9.95 |
| 647 | 10.30 |
| 663 | 10.45 |
| 724 | 11.12 |
| 791 | 12.30 |
| 873 | 13.80 |
| CURVE 16 | |
| 295 | 4.78* |
| 314 | 5.02 |
| 321 | 5.14 |
| 332 | 5.33 |
| 359 | 5.56 |
| 377 | 5.88 |
| 394 | 6.05 |
| 411 | 6.30 |
| 451 | 7.33 |
| 464 | 7.53 |
| 535 | 8.36 |
| 555 | 8.73 |
| 563 | 9.04 |
| 616 | 9.59 |
| 631 | 9.87 |
| 670 | 10.59 |
| 725 | 11.23 |
| 773 | 12.05 |
| 836 | 13.05 |
| 873 | 13.88 |
| 878 | 14.00 |

* Not shown in figure.

4.4. Strontium

Strontium, with atomic number 38, is a silvery-white metal, resembling calcium in its properties but softer. It exists in three structural modifications: face-centered cubic α -Sr stable below 488 K, close-packed hexagonal β -Sr stable between 488 and 815 K, and body-centered cubic γ -Sr stable above 815 K. The density of α -Sr is 2.60 g cm^{-3} at 293 K. The metal melts at 1042 K and boils at about 1645 K. At room temperature and a high pressure of $3.5 \times 10^9 \text{ Pa}$, α -Sr undergoes a phase transformation to a body-centered cubic structure similar to γ -Sr. Naturally occurring strontium is composed of four stable isotopes, the most abundant being ^{88}Sr which constitutes 82.56%. Twelve other radioactive isotopes are known to exist, one of which, the longest-lived ^{90}Sr with a half life of 28.1 years, is of great importance. This radioactive isotope is one of the best long-lived high energy beta emitters known and is very useful. But it also is a product of nuclear fallout and presents a health problem. Strontium is the fifteenth most abundant element in the continental crust of the earth (0.0375% by weight).

Temperature Dependence

There are 11 sets of experimental data available for the temperature dependence of the electrical resistivity of strontium. The information on specimen characterization and measurement condition for each of the data sets is given in Table 13. The data are tabulated in Table 14 and shown in Figures 8 and 9. Determinations of the electrical resistivity for both the solid and liquid states cover the temperature range from 1.32 to 1093 K.

The data of Messiner and Voigt [27] (curves 8 and 9), Rinck [76] (curve 11), McWhan, Rice, and Schmidt [77] (curves 1-3), and Rashid and Kayser [78] (curve 4) were not for high-purity specimens. At temperatures below 815 K the recommended values are based on the data of Cook and Van der Meer [73] (curve 6), Rashid and Kayser [78] (curve 5), and Katerberg et al. [68] (curve 10). These three sets of data for 99.5% pure specimens appear to be reasonably consistent. A least-mean-square-error fit was made with the modified Bloch-Grüneisen equation (8) to the selected data for ρ - ρ_0 from 50 to 800 K. The following results were obtained for the coefficients in equation (8):

| S_1 | S_2 | S_3 | $(\theta_R)_0$ | C | P |
|--|---|-------|----------------|--------|---|
| $6.015 \cdot 10^{-8} \Omega \text{ m}$ | $-0.02743 \cdot 10^{-8} \Omega \text{ m}$ | 0 | 142.7 K | 0.0108 | 0 |

The Debye temperature deduced from specific heat measurements is 147 K which is very

close to the present value for θ_R . The resulting values from equation (8) were then corrected for thermal linear expansion to become the final recommended values.

There appears to be no discontinuity in the electrical resistivity at the temperature of 488 K where the transition from α -Sr to β -Sr occurs. However, at the β -Sr to γ -Sr transition around 815 K, there is a sudden jump of about 40% in the resistivity values. Above 815 K the recommended resistivity values are based on the data of Katerberg et al. [68] (curve 10). Their data were fitted with a linear logarithmic equation up to the melting point resulting in the following equation:

$$\log_{10} \rho = -1.6233 + 1.137 \times \log_{10} T \quad 815 \text{ K} \leq T \leq 1042 \text{ K} \quad (13)$$

Only one set of data is available on the electrical resistivity of strontium in the liquid state. Van Zytveld et al. [50] (curve 7) found that the temperature dependence of electrical resistivity is small and weakly negative. At the melting point (1042 K), the electrical resistivity of strontium in the liquid state is about 31% higher than that of solid strontium.

The recommended values for the total and intrinsic electrical resistivities of strontium are listed in Table 12, and those for the total electrical resistivity are also shown in Figures 8 and 9. The recommended values for the total electrical resistivity are for 99.95% pure strontium and those at temperatures below 30 K are applicable only to a specimen with residual resistivity of $0.80 \times 10^{-8} \Omega \text{ m}$. The recommended values from 1 to 293 K are corrected for the thermal linear expansion. The correction amounts to -0.54% at 1 K, -0.42% at 100 K, and -0.21% at 200 K. The uncertainty in the recommended values for the total electrical resistivity is believed to be within $\pm 10\%$ below 50 K, within $\pm 5\%$ from 50 to 815 K, within $\pm 10\%$ from 815 K to 1042 K and within $\pm 20\%$ above 1042 K. Above 40 K, the uncertainty in the recommended values for the intrinsic resistivity is slightly higher than that in the total electrical resistivity because of the possible deviations from the Matthiessen's Rule; below 40 K ρ_i values are very uncertain and are not listed in the table.

TABLE 12. RECOMMENDED ELECTRICAL RESISTIVITY OF STRONTIUM
(Temperature Dependence)

[Temperature, T, K; Total Resistivity, ρ , $10^{-8} \Omega \cdot \text{m}$; Intrinsic Resistivity, ρ_i , $10^{-8} \Omega \cdot \text{m}$]

| Solid | | | | | |
|-------|--------|----------|--------|--------|----------|
| T | ρ | ρ_i | T | ρ | ρ_i |
| 1 | 0.800* | | 250 | 11.3 | 10.5 |
| 4 | 0.800* | | 273.15 | 12.3 | 11.5 |
| 7 | 0.800* | | 293 | 13.2 | 12.4 |
| 10 | 0.805* | | 300 | 13.5 | 12.7 |
| 15 | 0.835* | | 350 | 15.7 | 14.9 |
| 20 | 0.918* | | 400 | 17.8 | 17.0 |
| 25 | 1.065* | | 450 | 20.0 | 19.2 |
| 30 | 1.257* | | 500 | 22.2 | 21.4 |
| 35 | 1.460* | | 550 | 24.5 | 23.7 |
| 40 | 1.700* | | 600 | 26.7 | 25.9 |
| 45 | 1.94* | 1.14* | 650 | 28.9 | 28.1 |
| 50 | 2.18 | 1.38 | 700 | 31.2 | 30.4 |
| 60 | 2.68 | 1.88 | 750 | 33.4 | 32.6 |
| 70 | 3.16 | 2.36 | 800 | 35.6 | 34.8 |
| 80 | 3.64 | 2.84 | 815 | 36.1 | 35.3 |
| 90 | 4.12 | 3.32 | 815 | 48.8* | 48.0* |
| 100 | 4.58 | 3.78 | 950 | 54.5* | 53.7* |
| 110 | 5.04 | 4.24 | 1000 | 62.2* | 61.4* |
| 120 | 5.50 | 4.70 | 1042 | 65.6* | 64.8* |
| 130 | 5.94 | 5.14 | | | |
| 140 | 6.39 | 5.59 | | | |
| 150 | 6.84 | 6.04 | | | |
| 175 | 7.95 | 7.15 | | | |
| 200 | 9.04 | 8.24 | | | |
| 225 | 10.2 | 9.35 | | | |

| Liquid | |
|--------|--------|
| T | ρ |
| 1042 | 84.8* |
| 1093 | 84.7* |

* Provisional values

The recommended values for the total electrical resistivity are for 99.95+% pure strontium and those at temperatures below 30 K are applicable only to a specimen with residual resistivity of $0.80 \times 10^{-8} \Omega \cdot \text{m}$.

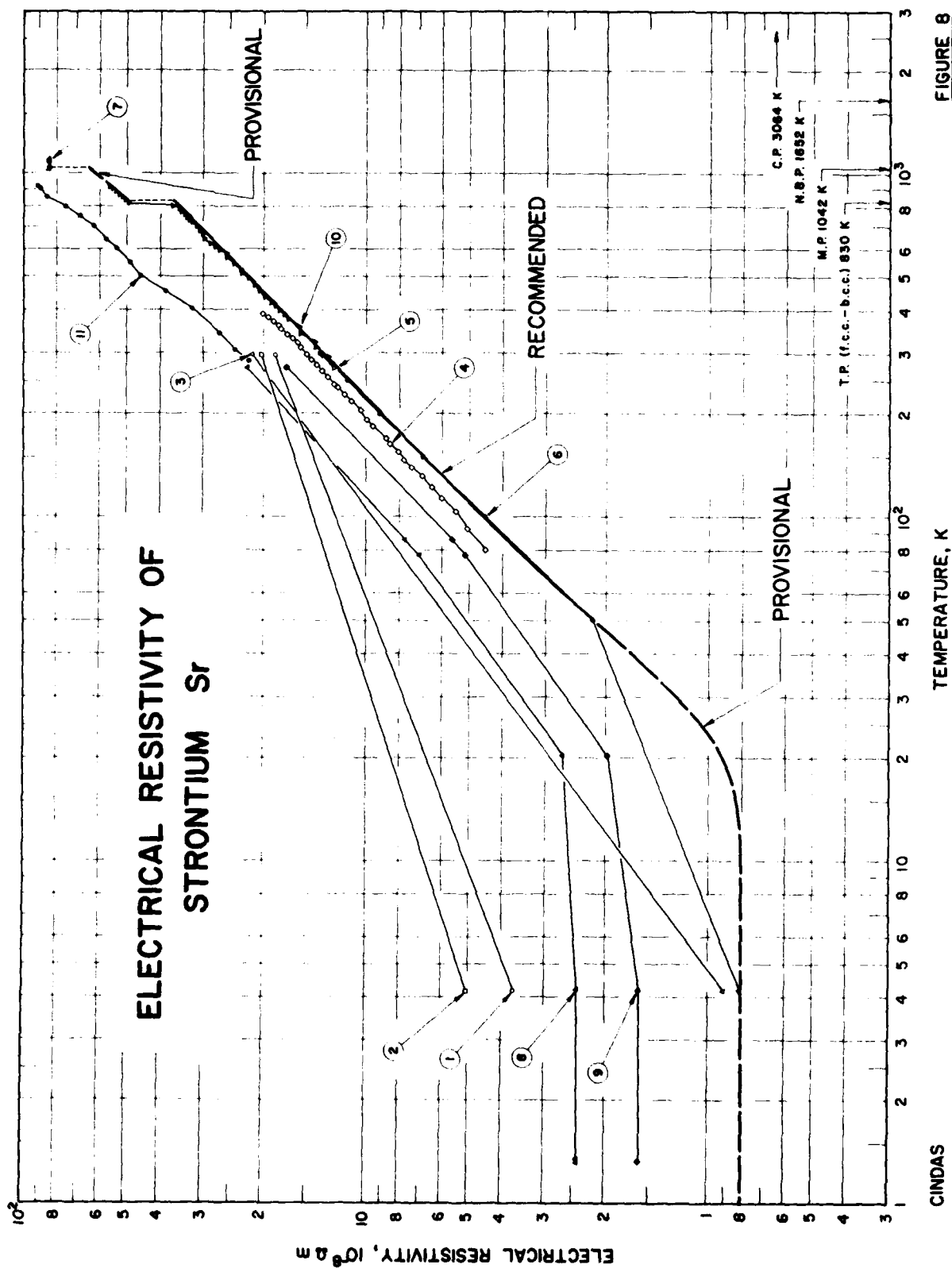


FIGURE 8

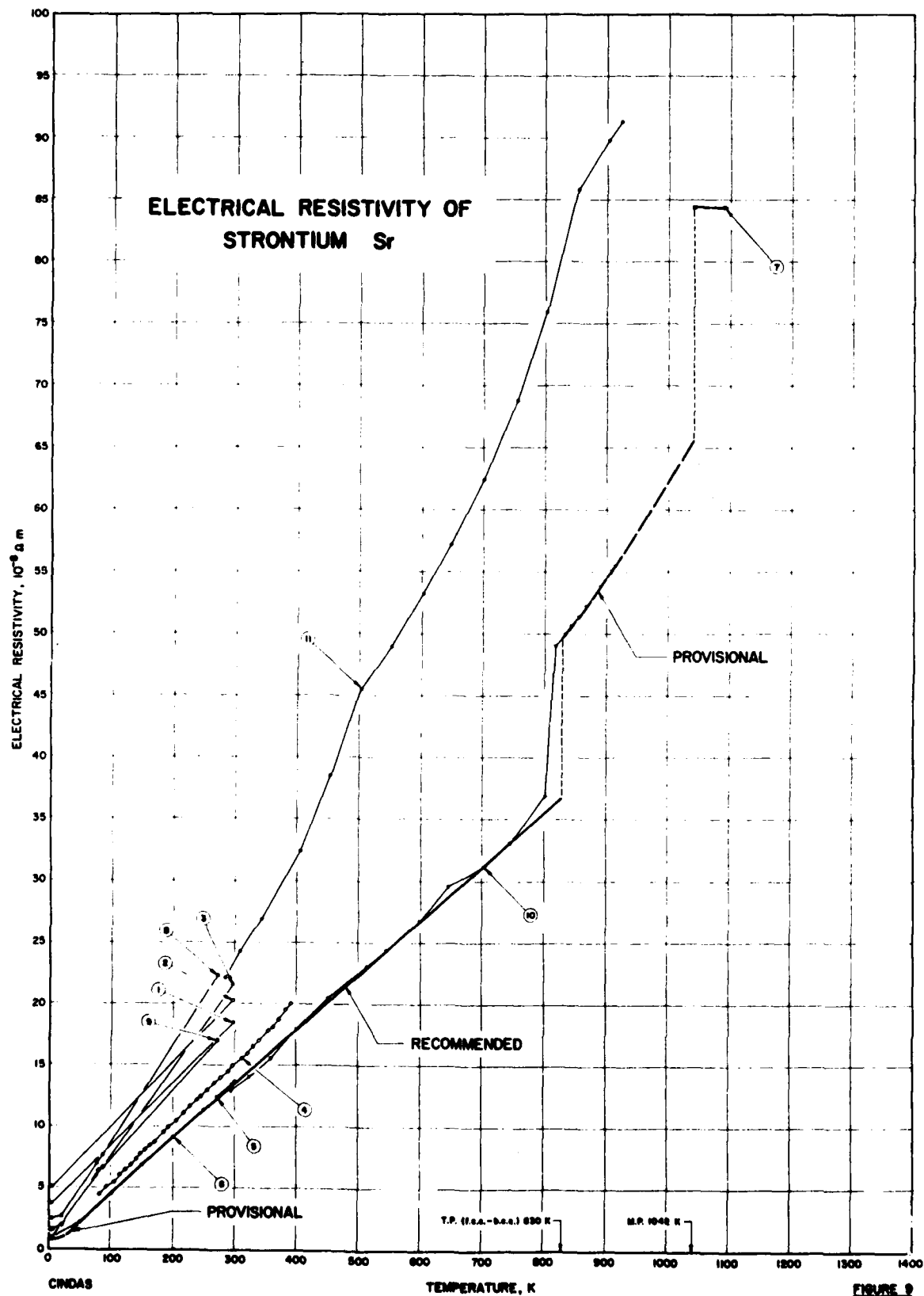


FIGURE 9

TABLE 13. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF STRONTIUM Sr (Temperature Dependence)

| Cur. Ref. No. | Author(s) | Year | Method Used | Temp. Range, K | Name and Specimen Designation | Composition (weight percent), Specifications, and Remarks |
|---------------|---|------|-------------|----------------|-------------------------------|---|
| 1 77 | McWhan, D. B., Rice, T. M., and Schmidt, P. H. | 1969 | A | 4.2-298 | Sr 4 | 98.1 Sr, 1.9 (Mg, Ca, Ba), 0.04 other; $R_{298}/4.2 = 5$; samples were made from metal purified by fractional distillation. |
| 2 77 | McWhan, D. B., et al. | 1969 | A | 4.2-298 | Sr 5 | 98.8 Sr, 1.2 (Mg, Ca, Ba), 0.05 other; $R_{298}/4.2 = 4$. |
| 3 77 | McWhan, D. B., et al. | 1969 | A | 4.2-298 | Sr 6 | 98.6 Sr, 1.4 (Mg, Ca, Ba), 0.03 other; $R_{298}/4.2 = 24$. |
| 4 78 | Rashid, M. S. and Kayser, F. X. | 1971 | | 80-400 | Sr | 98* Sr, 0.2 each Ba, Ca, 0.025 Mg, 0.03 each Fe, Ni, 0.015 Al, 0.05 (Li + Na + K); 3.8 mm diameter, 10 mm long wire specimen annealed at 470 K for 16 hr, 3 times. |
| 5 78 | Rashid, M. S. and Kayser, F. X. | 1971 | | 273, 298 | Sr (distilled) | Same as above except the specimen was distilled at 1140 K. |
| 6 73 | Cook, J. G. and Van der Meer, M. P. | 1973 | | 4.2-300 | Sr | 99* purity; $\rho(273.2)/\rho(4.2) = 15.5$ |
| 7 50 | Van Zytveld, J. B., Endrby, J. E., 1972 and Collings, E. M. | 1972 | | 1043-1093 | Sr | 99.5 pure, < 0.08 Fe, 0.05 each Al, Ni, Ba, Mg, Ca, 0.01 Cl ₂ , 0.1 others; specimen was obtained from Atomergic Chemicals Co. |
| 8 27 | Meissner, W. and Voigt, B. | 1930 | - | 1.32-273 | Sr 1 | < 0.1 Fe; specimen was in a glass tube with helium; specimen size was 0.5 x 2.5 x 34 mm; the electrical resistance was measured by compensation method with a mirror galvanometer; no thermal expansion correction for electrical resistivity data. |
| 9 27 | Meissner, W. and Voigt, B. | 1930 | - | 1.32-273 | Sr 2 | Similar to the above specimen except it was heated in vacuo for 3 hr at 160 C. |
| 10 68 | Kuerberg, J., Niemeyer, S., Penning, D., and Van Zytveld, J. B. | 1975 | A | 294-912 | | 99.5-99.7 purity specimen was obtained from Atomergic Chemicals Co.; the measurements were taken with sample held under an atm of pure inert gas; data were extracted from figure. |
| 11 76 | Rinck, E. | 1952 | A | | | Pure, double distilled specimen was obtained from Pechiney Co.; cylindrical specimen about 10 cm long; melting point 1041 K; data were extracted from graph. |

TABLE 14. EXPERIMENTAL DATA ON THE ELECTRICAL RESISTIVITY OF STRONTIUM
[Temperature, T, K; Resistivity, ρ , 10^{-8} Ohm]

| Sr (Temperature Dependence) | | | | | |
|-----------------------------|--------|--|------------------------|-----------------|--|
| T | ρ | | T | ρ | |
| <u>CURVE 1</u> | | | <u>CURVE 4 (cont.)</u> | | |
| 4.2 | 3.7 | | 302.6 | 15.13* | |
| 298 | 18.5 | | 312.2 | 15.59 | |
| <u>CURVE 2</u> | | | 317.1 | 15.77* | |
| 4.2 | 5.08 | | 321.7 | 15.92 | |
| 298 | 20.3 | | 326.7 | 16.09* | |
| <u>CURVE 3</u> | | | 330.8 | 16.53 | |
| 4.2 | 0.90 | | 335.6 | 16.71* | |
| 298 | 21.6 | | 340.1 | 17.03 | |
| <u>CURVE 4</u> | | | 344.9 | 17.22* | |
| 60.2 | 4.49 | | 349.6 | 17.35* | |
| 92.8 | 5.07 | | 353.9 | 17.82 | |
| 104.1 | 5.47 | | 358.5 | 17.99* | |
| 117.9 | 6.02 | | 362.8 | 18.17 | |
| 122.9 | 6.42 | | 367.3 | 18.31* | |
| 132.1 | 6.86 | | 371.6 | 18.77 | |
| 140.1 | 7.35 | | 377.4 | 18.96* | |
| 157.8 | 7.76 | | 379.7 | 19.24* | |
| 155.4 | 8.09 | | 383.6 | 19.53 | |
| 162.1 | 8.51 | | 398.1 | 19.80* | |
| 170.9 | 8.78 | | 391.0 | 20.05 | |
| 184.8 | 9.55 | | <u>CURVE 5</u> | | |
| 192.2 | 9.93 | | 272.7 | 12.46 | |
| 198.8 | 10.13* | | 297.9 | 13.46 | |
| 205.0 | 10.47 | | <u>CURVE 6</u> | | |
| 211.1 | 10.73* | | 4.2 | 0.906 | |
| 217.1 | 11.07 | | 50 | 2.18 | |
| 222.6 | 11.35* | | 100 | 4.50 | |
| 228.9 | 11.64 | | 150 | 6.82 | |
| 234.3 | 11.89* | | 200 | 9.12 | |
| 239.7 | 12.15 | | 250 | 11.38 | |
| 245.9 | 12.43 | | 273 | 12.5* | |
| 251.2 | 12.62* | | 300 | 13.65 | |
| 256.3 | 12.98 | | <u>CURVE 7</u> | | |
| 262.0 | 13.25* | | 1043 | 84.8 \pm 2.0 | |
| 267.4 | 13.49 | | 1093 | 84.65 \pm 2.0 | |
| 272.2 | 13.75* | | <u>CURVE 8</u> | | |
| 277.4 | 13.99 | | 1.32 | 2.416 | |
| 282.9 | 14.29* | | 1.35 | 2.416 | |
| 288.0 | 14.50 | | 4.21 | 2.416 | |
| 292.4 | 14.69* | | | | |
| 297.7 | 14.97* | | | | |

*Not shown in figure.

4.5. Barium

Barium, with atomic number 56, is a soft, silver-white metal, resembling calcium chemically. It oxidizes very easily in air, melts at 1002 K, and boils at 2174 K. Its density is 3.5 g cm^{-3} at 293 K. The critical temperature of barium has been estimated to be 3670 K. Barium crystal has a body-centered cubic structure. At a pressure of about $5.9 \times 10^9 \text{ Pa}$, the body-centered cubic structure transforms to a close-packed hexagonal form. Naturally occurring barium is composed of seven stable isotopes, the most abundant being ^{138}Ba , which constitutes 71.66%. Thirteen other radioactive isotopes are known to exist. Barium is the fourteenth most abundant element in the continental crust of the earth (0.0524% by weight).

Temperature dependence

There are 21 sets of experimental data available for the electrical resistivity of barium. The information on specimen characterization and measurement condition for each of the data sets is given in Table 16. The data are tabulated in Table 17 and shown in Figures 10 and 11. Determinations of the electrical resistivity for both the solid and liquid states cover continuously the temperature range from 1.26 to 1451 K.

The data for the electrical resistivity of barium show considerable scatter. At low temperatures, the data of Meissner and Voigt [27] (curve 5), Meissner, Franz, and Westerhoff [79] (curve 10), and of Rashid and Kayser [80] (curves 6 and 7) are not for high-purity specimen. Above room temperature, Rinck [81] found a distinct slope change about 650 K (curve 13) which he assumed to be due to phase change at this temperature. The data of Grüntherodt, Hause, and Kunzi [82] (curve 9) are similar to Rinck's. The data of Grube and Dietrich [83] (curve 14) also show a discontinuity near 650 K, which however, exhibits quite a different nature from that indicated by the data of Rinck. The data of Katerberg, Nieneyer, Penning, and Van Zytveld [68] (curves 11 and 12) show no slope change at 650 K, but show a slope change near 530 K. Cook and Laubitz [84] presented data for pure and hydrogen charged Ba from 300 to 750 K (curves 15-21). Their data for pure barium differ from all previous data and show no evidence of transition at any temperature.

A least-mean-square-error fit was made with the modified Bloch-Grüneisen equation (8) to the data of Cook and Laubitz [84] (with correction for the effect of hydrogen) and of Rashid and Kayser [80] (curve 8) from 30 to 750 K. The following results were obtained for the coefficients in equation (8):

| S_1 | S_2 | S_3 | $(\rho_R)_0$ | C | P |
|---|--|-------|--------------|--------|---|
| $5.870 \cdot 10^{-8} \Omega \cdot \text{m}$ | $0.3428 \cdot 10^{-8} \Omega \cdot \text{m}$ | 0 | 72.8 K | 0.0252 | 0 |

The Debye temperature deduced from specific heat measurements is 110 K which is almost 40% higher than the present value for ρ_R . The resulting values from equation (8) were then corrected for the thermal linear expansion and extrapolated to lower and higher temperatures to become the final recommended values.

There are three data sets available on the electrical resistivity of barium in the liquid state. Van Zytveld, Enderberg, and Collings [50] (curve 3) and Grüntherodt et al. [82] (curve 9) found that the temperature dependence of the electrical resistivity of liquid barium is small and weakly negative. However, Genter and Grosse [85] (curve 2) found a very large positive temperature dependence. On comparison with the electrical resistivity data for other alkaline earth elements in the liquid state, indicated that the electrical resistivity of liquid barium should have a weakly negative dependence on temperature. The data of Van Zytveld et al. and of Grüntherodt et al. were normalized by matching their values at the melting point of 1002 K. The normalized values were then least-mean-square-error fitted with a linear equation to yield the provisional values. At the melting point (1002 K), the electrical resistivity of barium in the liquid state is about 25% higher than that of solid barium.

The recommended values for the total and intrinsic electrical resistivities are listed in Table 15, and those for the total resistivity are also shown in Figures 10 and 11. The recommended values for the total electrical resistivity are for 99.5+% pure barium and those at temperatures below 100 K are applicable only to a specimen with residual resistivity of $0.081 \times 10^{-8} \Omega \cdot \text{m}$. The recommended values from 1 to 293 K are corrected for the thermal linear expansion. The correction amounts to -0.5% at 1 K, -0.37% at 100 K, and -0.18% at 200 K. The uncertainty in the recommended values for the total electrical resistivity is believed to be within $\pm 10\%$ below 30 K, within $\pm 5\%$ from 30 to 750 K, and within $\pm 10\%$ from 750 to 1300 K. Above 40 K the uncertainty in the recommended values for the intrinsic resistivity is slightly higher than that in the total electrical resistivity because of the possible deviations from the Matthiessen's Rule; below 40 K, the ρ_i values are very uncertain and are not listed in the table.

TABLE 15. RECOMMENDED ELECTRICAL RESISTIVITY OF BARIUM
(Temperature Dependence)

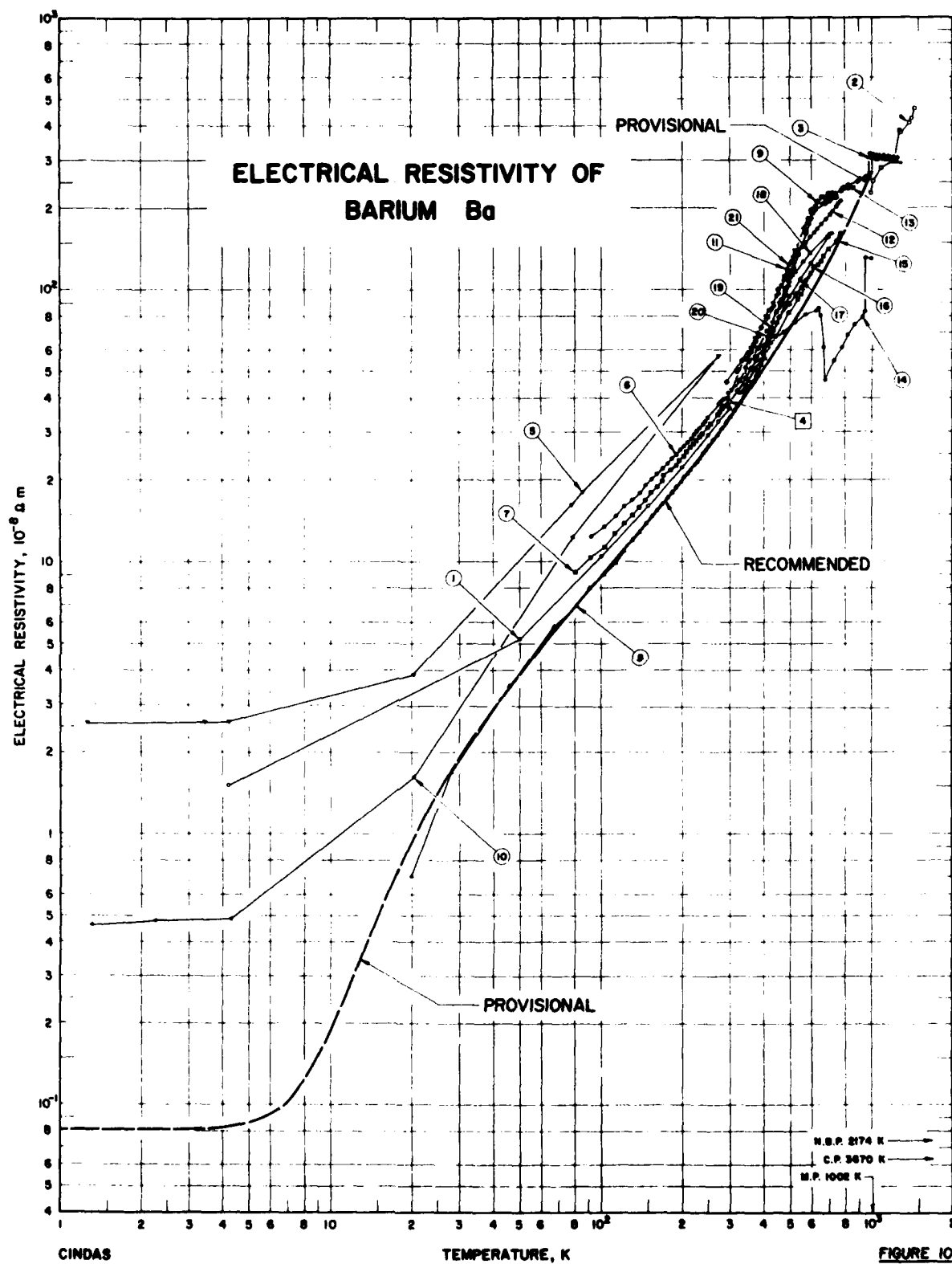
[Temperature, T, K; Total Resistivity, ρ , $10^{-8} \Omega \cdot \text{m}$; Intrinsic Resistivity, ρ_i , $10^{-8} \Omega \cdot \text{m}$]

| Solid | | | | | |
|-------|--------|----------|--------|--------|----------|
| T | ρ | ρ_i | T | ρ | ρ_i |
| 1 | 0.081* | | 250 | 26.9 | 26.8 |
| 4 | 0.082* | | 273.15 | 30.2 | 30.1 |
| 7 | 0.104* | | 293 | 33.2 | 33.1 |
| 10 | 0.189* | | 300 | 34.3 | 34.2 |
| 15 | 0.501* | | 350 | 42.4 | 42.3 |
| 20 | 0.940* | | 400 | 51.4 | 51.3 |
| 25 | 1.42 * | | 450 | 61.4 | 61.3 |
| 30 | 1.92 * | | 500 | 72.4 | 72.3 |
| 35 | 2.41 * | | 550 | 84.7 | 84.6 |
| 40 | 2.91 * | | 600 | 98.2 | 98.1 |
| 45 | 3.39 | 3.31 | 650 | 113. | 113. |
| 50 | 3.88 | 3.80 | 700 | 130. | 130. |
| 60 | 4.86 | 4.78 | 750 | 148. | 148. |
| 70 | 5.84 | 5.76 | 800 | 168. * | 168. * |
| 80 | 6.83 | 6.75 | 900 | 216. * | 216. * |
| 90 | 7.83 | 7.75 | 950 | 244. * | 244. * |
| 100 | 8.85 | 8.77 | 1000 | 275. * | 275. * |
| 110 | 9.89 | 9.81 | 1002 | 276. * | 276. * |
| 120 | 11.0 | 10.9 | | | |
| 130 | 12.0 | 11.9 | | | |
| 140 | 13.1 | 13.0 | | | |
| 150 | 14.3 | 14.2 | | | |
| 175 | 17.2 | 17.1 | | | |
| 200 | 20.2 | 20.1 | | | |
| 225 | 23.5 | 23.4 | | | |

| Liquid | | |
|--------|--------|---|
| T | ρ | |
| 1002 | 306. | * |
| 1050 | 303. | * |

* Provisional values

The recommended values for the total electrical resistivity are for 99.5+% pure barium and those at temperatures below 100 K are applicable only to a specimen with residual resistivity of $0.081 \times 10^{-8} \Omega \cdot \text{m}$.



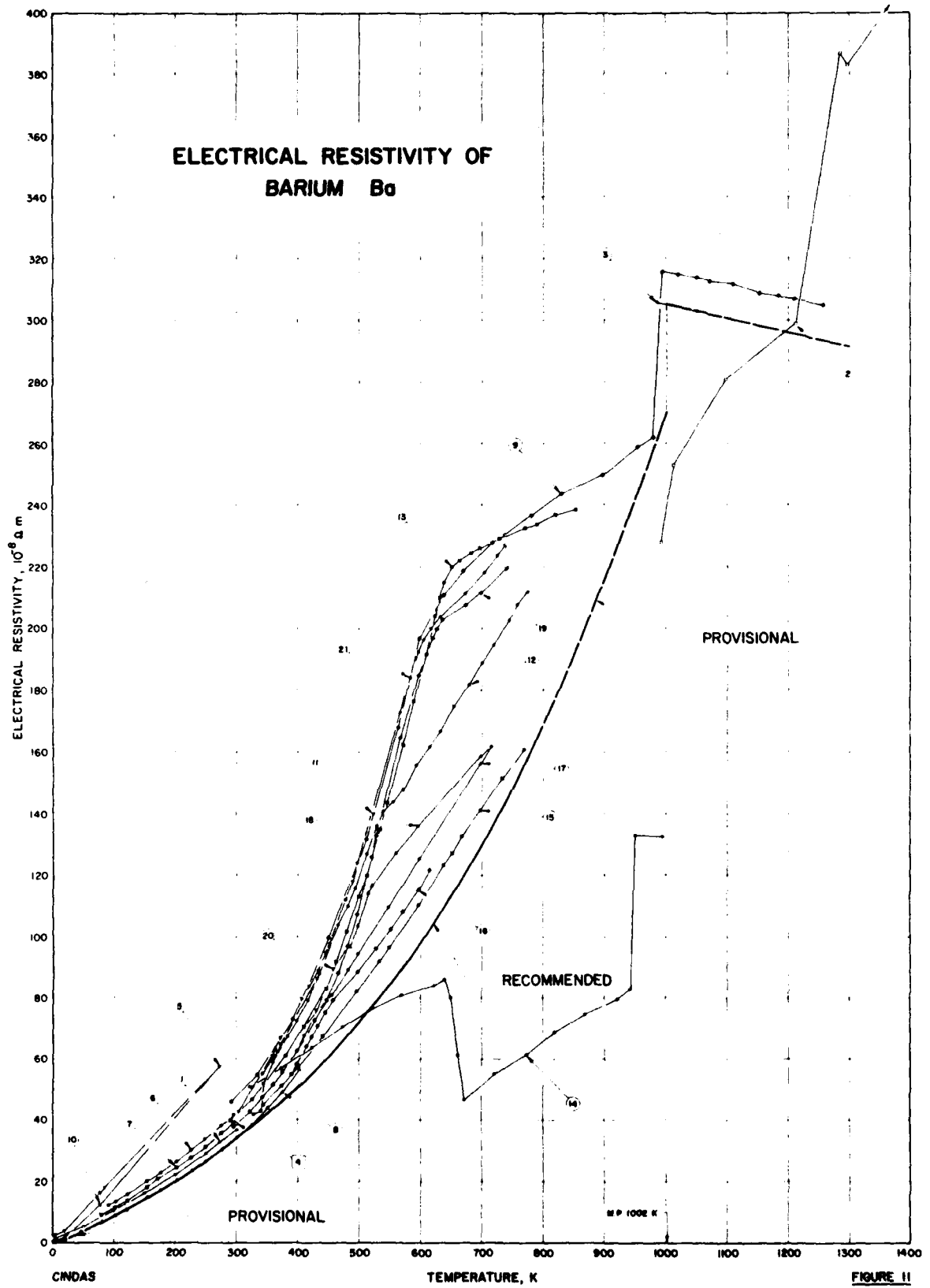


TABLE 16. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF BARIUM Ba (Temperature Dependence)

| Cur. Ref. No. | Author(s) | Year | Method Used | Temp. Range, K | Name and Specimen Designation | Composition (weight percent), Specifications, and Remarks |
|---------------|--|------|-------------|----------------|-------------------------------|--|
| 1 | 73 Cook, J. G. and Van der Meer, M. P. | 1973 | | 4.2-300 | | 99.9 purity; $\rho(273)/\rho(4.2) = 21.8$; data were extracted from the smooth table. |
| 2 | 85 Gemter, R. B. and Grosse, A. V. | 1971 | | 993-1500 | | 99.97 pure, 0.03 each Ca, Sr; liquid barium was contained in a Type 304 stainless steel tube about 0.5 in O.D., 0.421 in I.D. and 10 in. long; the sample was obtained from Mackay Metals, New York. |
| 3 | 50 Van Zyrveld, J. B., Enderby, J. E., and Collings, E. M. | 1972 | | 988, 1053 | | 99.5 Ba, <0.1 each Sr, Na, C, <0.05 each Al, Fe, N ₂ , Zn; specimen was obtained from Atomergic Chemicals Co. |
| 4 | 86 Müller, W. E. | 1967 | | 300 | | Pure; |
| 5 | 27 Meissner, W. and Voigt, B. | 1930 | | 1.25-273 | Ba 1 | Pure; specimen was placed in a glass tube filled with helium; sample size 0.2 x 4 x 40 mm; the electrical resistance was measured by compensation method, a mirror galvanometer was used. |
| 6 | 80 Rashid, M. S. and Kayser, F. X. | 1971 | A | 80-300 | 1 | 99.0 pure Ba bar was obtained from Charles Pfizer Co., Inc.; it was extruded to 0.254 cm diameter wire and 3 cm long specimen; the specimen was in b.c.c. structure. |
| 7 | 80 Rashid, M. S. and Kayser, F. X. | 1971 | A | 80-300 | 2 | Similar to the above specimen except it was in recrystallized treatment at 470 K for 16 hr. |
| 8 | 80 Rashid, M. S. and Kayser, F. X. | 1971 | A | 20-400 | 3 | Similar to the above specimen except it was double distilled and annealed at 400 K for 4 days; $\rho(300 \text{ K})/\rho(4.2 \text{ K}) = 400 \sim 900$. |
| 9 | 82 Güntherodt, H. J., Hauser, E., and Künzi, H. V. | 1975 | C | 292-1258 | | 99.5 pure; the specimen was supplied by Fluka; a thin-wall vacuum tight stainless steel crucible was used in measurement; the specimens were etched first in methyl alcohol and then in toluene, then the specimens were transferred to the measuring cell and the open end of the crucible was pressed together; data were extracted from the figure; reported error 4%. |
| 10 | 79 Meissner, W., Franz, H., and Westerhoff, H. | 1932 | | 1.3-273.16 | | Pure; the specimen was obtained from Dr. Friderich; relative resistance data were reported; resistance at temperature 273.16 K, $R_0 = 3.12 \times 10^{-3} \Omega$; the resistivity data were obtained by using $\rho_{\text{Cu}}/\rho_{\text{Ba}} = 57.6 \times 10^{-4} \Omega \cdot \text{m}$. |
| 11 | 68 Kzerberg, J., Niemeyer, S., Penning, D., and Van Zyrveld, J. B. | 1975 | A | 295-524 | | 99.5-99.7 purity specimen was obtained from Atomergic Chemicals Co.; the experiment was measured with the sample held under an atm of pure argon; data were extracted from figure. |
| 12 | 68 Kzerberg, J., et al. | 1975 | A | 328-776 | | Similar to the above specimen. |
| 13 | 81 Rinck, F. | 1931 | A | | | Pure; double distilled specimen was prepared by Prof. Guntz; cylindrical specimen 10 cm long, 1.215 cm in diameter; because of crack only small section of the specimen was used to measure the resistance; melting point 984 K; data were extracted from figure. |
| 14 | 63 Grube, G. and Dietrich, A. | 1938 | | 322-995 | | 98.72 Ba, 0.31 Mg, 0.18 Zn, 0.25 Si, 0.05 Fe + Al, 0.33 Cl, rest N ₂ + O ₂ ; melting point 930 \pm 2 K; the specimen was obtained from I. G. Farbenindustrie Aktiengesellschaft, Bitterfeld. |
| 15 | 84 Cook, J. G. and Laubitz, M. J. | 1976 | | 344-770 | Ba3 | Pure; specimen was prepared by sublimation at 1173 K in He at 8 mm Hg, a 405 stainless steel pot was used; a Ta tube degassed at 1173 K was filled with Ba dendrites and welded shut at both ends and it was kept at 1173 K in vacuum for three days in order to drive off as much H as possible, finally the Ta was removed from the Ba casting using a tube in a glove box containing inert gas; the residual resistance ratio of the sample was 55; measurements were taken with increasing temperature; data were extracted from the smooth figure; no thermal expansion correction on data. |

TABLE 16. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF BARIUM Ba (Temperature Dependence) (continued)

| Ref. No. | Author(s) | Year | Method Used | Temp. Range, K | Name and Specimen Designation | Composition (weight percent), Specifications, and Remarks |
|----------|------------------------------|------|-------------|----------------|-------------------------------|---|
| 16 84 | Cook, J.G. and Laubitz, M.J. | 1976 | | 344-615 | Ba3 | The above specimen; the sample was first cooled to 620 K and after a 10 hr period measurements were taken with decreasing temperature. |
| 17 84 | Cook, J.G. and Laubitz, M.J. | 1976 | | 423-716 | Ba3 | The above specimen was allowed to react with H ₂ at 535 K; measurements were taken with increasing temperature. |
| 18 84 | Cook, J.G. and Laubitz, M.J. | 1976 | | 485-716 | Ba3 | The above specimen; measurements were taken with decreasing temperature. |
| 19 84 | Cook, J.G. and Laubitz, M.J. | 1976 | | 295-742 | Ba3 | The above specimen was allowed for H ₂ charging at 620 K; measurements were taken with increasing temperature. |
| 20 84 | Cook, J.G. and Laubitz, M.J. | 1976 | | 295-742 | Ba3 | The above specimen; measurements were taken with decreasing temperature. |
| 21 84 | Cook, J.G. and Laubitz, M.J. | 1976 | | 324-739 | Ba2 | Commercially pure; residual resistance ratio was 10; data were extracted from the smooth figure and without thermal expansion correction. |

TABLE 17. EXPERIMENTAL DATA ON THE ELECTRICAL RESISTIVITY OF BARIUM Ba (Temperature Dependence)
[Temperature, T, K; Resistivity, ρ , 10^{-9} (cm)]

| CURVE 1 | | | CURVE 6 (cont.) | | | CURVE 7 (cont.) | | | CURVE 8 (cont.) | | | CURVE 9 (cont.) | | | CURVE 10 | | | CURVE 11 | | | CURVE 12 (cont.) | | |
|---------|----------------|--|-----------------|--------|--|-----------------|--------|--|-----------------|--------|--|-----------------|--------|--|----------|--------|--|----------|--------|--|------------------|--------|--|
| T | ρ | | T | ρ | | T | ρ | | T | ρ | | T | ρ | | T | ρ | | T | ρ | | T | ρ | |
| 4.2 | 1.51 | | 139 | 17.9 | | 250 | 31.4 | | 301 | 34.3 | | 1154 | 309 | | CURVE 10 | | | 295 | 40.1 | | 573 | 148 | |
| 50 | 3.21 | | 146 | 19.1 | | 255 | 32.2 | | 306 | 35.2* | | 1155 | 308 | | CURVE 11 | | | 306 | 44.3 | | 594 | 156 | |
| 100 | 10.31 | | 154 | 20.1 | | 271 | 34.8 | | 311 | 36.2 | | 1211 | 307 | | CURVE 12 | | | 326 | 51.4 | | 616 | 162 | |
| 150 | 16.14 | | 161 | 21.0 | | 276 | 35.8 | | 316 | 36.9* | | 1258 | 305 | | CURVE 13 | | | 342 | 57.1* | | 633 | 167 | |
| 200 | 22.34 | | 170 | 22.0 | | 281 | 36.7 | | 320 | 37.8 | | CURVE 14 | | | CURVE 10 | | | 357 | 62.4 | | 655 | 173 | |
| 250 | 29.25 | | 176 | 23.0 | | 286 | 37.7 | | 325 | 38.5 | | CURVE 15 | | | CURVE 11 | | | 372 | 67.2 | | 693 | 178 | |
| 273 | 33.0 | | 183 | 24.0 | | 296 | 39.3 | | 331 | 39.3 | | CURVE 16 | | | CURVE 12 | | | 391 | 73.3* | | 701 | 189 | |
| 300 | 36.9 | | 190 | 24.8 | | CURVE 8 | | | 333 | 40.3* | | CURVE 17 | | | CURVE 13 | | | 407 | 79.2 | | 720 | 195 | |
| CURVE 2 | | | 197 | 25.8 | | 20 | 0.7 | | 339 | 41.2* | | CURVE 18 | | | CURVE 14 | | | 419 | 83.3 | | 746 | 203 | |
| 593 | 229 | | 203 | 26.6 | | 28 | 1.7 | | 343 | 42.2 | | CURVE 19 | | | CURVE 15 | | | 434 | 89.3 | | 759 | 208 | |
| 1012 | 252 | | 209 | 27.5 | | 46 | 3.5 | | 348 | 43.2* | | CURVE 20 | | | CURVE 16 | | | 446 | 94.7 | | 776 | 212 | |
| 1099 | 281 | | 216 | 28.4 | | 67 | 5.8 | | 352 | 44.0 | | CURVE 21 | | | CURVE 17 | | | 462 | 106* | | CURVE 16 | | |
| 1212 | 299 | | 221 | 29.3 | | 81 | 6.9 | | 356 | 44.9* | | CURVE 22 | | | CURVE 18 | | | 489 | 118 | | CURVE 17 | | |
| 1296 | 387 | | 226 | 30.2 | | 91 | 8.0 | | 365 | 47.1* | | CURVE 23 | | | CURVE 19 | | | 527 | 140 | | CURVE 18 | | |
| 1298 | 383 | | 232 | 31.0 | | 102 | 9.0 | | 369 | 48.0* | | CURVE 24 | | | CURVE 20 | | | CURVE 19 | | | CURVE 19 | | |
| 1396 | 412 | | 238 | 32.0 | | 113 | 9.9 | | 376 | 49.1 | | CURVE 25 | | | CURVE 21 | | | CURVE 20 | | | CURVE 20 | | |
| 1412 | 420 | | 244 | 32.9 | | 122 | 11.0 | | 382 | 51.0 | | CURVE 26 | | | CURVE 22 | | | CURVE 21 | | | CURVE 21 | | |
| 1451 | 453 | | 249 | 34.0 | | 130 | 12.0 | | 386 | 52.2* | | CURVE 27 | | | CURVE 23 | | | CURVE 22 | | | CURVE 22 | | |
| CURVE 3 | | | 275 | 38.2 | | 139 | 12.8 | | 391 | 53.4 | | CURVE 28 | | | CURVE 24 | | | CURVE 23 | | | CURVE 23 | | |
| 989 | 306.0 ± 11 | | 280 | 39.1 | | 155 | 14.7 | | 395 | 54.5* | | CURVE 29 | | | CURVE 25 | | | CURVE 24 | | | CURVE 24 | | |
| 1053 | 302.4 ± 11 | | 285 | 40.0 | | 161 | 15.5 | | 399 | 55.7* | | CURVE 30 | | | CURVE 26 | | | CURVE 25 | | | CURVE 25 | | |
| CURVE 4 | | | 296 | 41.9 | | 176 | 16.3 | | 403 | 56.6 | | CURVE 31 | | | CURVE 27 | | | CURVE 26 | | | CURVE 26 | | |
| 306 | 39 | | CURVE 7 | | | 184 | 18.0 | | CURVE 9 | | | CURVE 32 | | | CURVE 28 | | | CURVE 27 | | | CURVE 27 | | |
| CURVE 5 | | | 90 | 9.2 | | 190 | 18.8 | | 282 | 46 | | CURVE 33 | | | CURVE 29 | | | CURVE 28 | | | CURVE 28 | | |
| 1.26 | 2.57 | | 92 | 10.4 | | 198 | 19.6 | | 334 | 55 | | CURVE 34 | | | CURVE 30 | | | CURVE 29 | | | CURVE 29 | | |
| 3.44 | 2.59 | | 103 | 11.4 | | 203 | 20.5 | | 383 | 73 | | CURVE 35 | | | CURVE 31 | | | CURVE 30 | | | CURVE 30 | | |
| 4.21 | 2.59 | | 113 | 12.8 | | 210 | 21.2 | | 451 | 100 | | CURVE 36 | | | CURVE 32 | | | CURVE 31 | | | CURVE 31 | | |
| 20.45 | 2.863 | | 131 | 14.9 | | 215 | 21.9 | | 513 | 122 | | CURVE 37 | | | CURVE 33 | | | CURVE 32 | | | CURVE 32 | | |
| 75.00 | 16.38 | | 146 | 16.9 | | 222 | 22.7 | | 565 | 166 | | CURVE 38 | | | CURVE 34 | | | CURVE 33 | | | CURVE 33 | | |
| 85.68 | 18.14 | | 154 | 18.0 | | 227 | 23.4 | | 599 | 197 | | CURVE 39 | | | CURVE 35 | | | CURVE 34 | | | CURVE 34 | | |
| 273.16 | 57.5 | | 162 | 18.8 | | 233 | 24.2 | | 639 | 211 | | CURVE 40 | | | CURVE 36 | | | CURVE 35 | | | CURVE 35 | | |
| CURVE 6 | | | 170 | 19.8 | | 238 | 25.1 | | 670 | 219 | | CURVE 41 | | | CURVE 37 | | | CURVE 36 | | | CURVE 36 | | |
| 92 | 12.4 | | 171 | 20.9 | | 244 | 25.9 | | 719 | 228 | | CURVE 42 | | | CURVE 38 | | | CURVE 37 | | | CURVE 37 | | |
| 103 | 13.5 | | 183 | 21.7 | | 250 | 26.6 | | 782 | 237 | | CURVE 43 | | | CURVE 39 | | | CURVE 38 | | | CURVE 38 | | |
| 114 | 14.7 | | 190 | 22.6 | | 254 | 27.4* | | 832 | 244 | | CURVE 44 | | | CURVE 40 | | | CURVE 39 | | | CURVE 39 | | |
| 122 | 16.0 | | 196 | 23.6 | | 261 | 28.2 | | 888 | 250 | | CURVE 45 | | | CURVE 41 | | | CURVE 40 | | | CURVE 40 | | |
| 130 | 16.9 | | 203 | 24.5 | | 266 | 28.7* | | 955 | 259 | | CURVE 46 | | | CURVE 42 | | | CURVE 41 | | | CURVE 41 | | |
| CURVE 7 | | | 209 | 25.3 | | 271 | 29.6 | | 980 | 262 | | CURVE 47 | | | CURVE 43 | | | CURVE 42 | | | CURVE 42 | | |
| 92 | 12.4 | | 215 | 26.2 | | 276 | 30.3 | | 995 | 316 | | CURVE 48 | | | CURVE 44 | | | CURVE 43 | | | CURVE 43 | | |
| 103 | 13.5 | | 220 | 27.0 | | 281 | 31.2 | | 1021 | 315 | | CURVE 49 | | | CURVE 45 | | | CURVE 44 | | | CURVE 44 | | |
| 114 | 14.7 | | 226 | 27.9 | | 287 | 31.9* | | 1051 | 314 | | CURVE 50 | | | CURVE 46 | | | CURVE 45 | | | CURVE 45 | | |
| 122 | 16.0 | | 233 | 28.8 | | 291 | 32.9 | | 1073 | 313 | | CURVE 51 | | | CURVE 47 | | | CURVE 46 | | | CURVE 46 | | |
| 130 | 16.9 | | 238 | 29.6 | | 295 | 33.5* | | 1111 | 312 | | CURVE 52 | | | CURVE 48 | | | CURVE 47 | | | CURVE 47 | | |

* Not shown in figure.

TABLE 17. EXPERIMENTAL DATA ON THE ELECTRICAL RESISTIVITY OF BARIUM Ba (Temperature Dependence) (continued)

| T | ρ | T | ρ | T | ρ |
|-------------------------|--------|-------------------------|--------|-----------------|--------|
| <u>CURVE 14 (cont.)</u> | | <u>CURVE 16 (cont.)</u> | | <u>CURVE 20</u> | |
| 423 | 64.0 | 532 | 102.5 | 295 | 38.0* |
| 472 | 70.7 | 572 | 108.3 | 322 | 42.8* |
| 523 | 76.7 | 598 | 115.6 | 343 | 47.5* |
| 570 | 81.0 | 615 | 121.9 | 360 | 51.5* |
| 623 | 84.1 | <u>CURVE 17</u> | | 375 | 55.8* |
| 639 | 85.9 | 423 | 67.3* | 399 | 62.7* |
| 650 | 80.3 | 432 | 70.9* | 411 | 67.7 |
| 661 | 61.4 | 456 | 81.1 | 431 | 76.0 |
| 672 | 46.9 | 482 | 89.2 | 458 | 89.7 |
| 721 | 55.2 | 498 | 94.6 | 479 | 101.7* |
| 773 | 61.5 | 545 | 109.7 | 498 | 113.4* |
| 819 | 66.9 | 598 | 125.5 | 528 | 133.0* |
| 869 | 74.7 | 699 | 156.6 | 568 | 164.6* |
| 922 | 79.8 | 716 | 161.9 | 598 | 184.9* |
| 942 | 83.0 | <u>CURVE 18</u> | | 620 | 197.1* |
| 950 | 132.9 | 435 | 96.9 | 627 | 200.1* |
| 995 | 132.7 | 498 | 103.8 | 637 | 203.1* |
| <u>CURVE 15</u> | | 516 | 114.4 | 674 | 207.8* |
| 344 | 44.9 | 521 | 116.6 | 700 | 211.9* |
| 374 | 51.4 | 560 | 127.1 | 742 | 219.9* |
| 390 | 55.1 | 587 | 136.3 | <u>CURVE 21</u> | |
| 400 | 57.1 | 699 | 159.0 | 324 | 50.6* |
| 441 | 67.6 | 716 | 161.9* | 343 | 55.4 |
| 497 | 82.3 | <u>CURVE 19</u> | | 368 | 62.5 |
| 524 | 92.1 | 295 | 38.0 | 384 | 67.6 |
| 550 | 96.6 | 322 | 42.8 | 399 | 72.6 |
| 598 | 110.6 | 343 | 47.5 | 417 | 79.5 |
| 638 | 123.6 | 360 | 51.5 | 431 | 86.6 |
| 658 | 127.5 | 375 | 55.8 | 453 | 97.8 |
| 688 | 132.0 | 399 | 62.7 | 479 | 112.2 |
| 698 | 141.4 | 428 | 72.7 | 498 | 124.2 |
| 734 | 151.6 | 447 | 79.4 | 568 | 172.8 |
| 770 | 161.0 | 466 | 88.3 | 584 | 184.3 |
| <u>CURVE 16</u> | | 482 | 97.0 | 598 | 192.7 |
| 344 | 44.9* | 498 | 107.6 | 606 | 196.5 |
| 374 | 51.4* | 528 | 133.0 | 618 | 200.2 |
| 390 | 55.1* | 568 | 164.6 | 634 | 204.1 |
| 415 | 64.3 | 598 | 184.9 | 674 | 211.5 |
| 423 | 67.3 | 620 | 197.1 | 706 | 218.3 |
| 432 | 70.9 | 627 | 200.1 | 726 | 223.8 |
| 446 | 75.4 | 674 | 207.8 | 739 | 227.0 |
| 459 | 79.4 | 700 | 211.9 | | |
| 498 | 88.7 | | | | |
| 528 | 96.3 | | | | |

* Not shown in figure.

4.6. RADIUM

Radium, with atomic number 88, is a brilliant white, radioactive metal, and is the last member of Group II A elements. Its density has been estimated to be about 5 g cm^{-3} , which is, however, questionable. The melting and boiling points of radium have been given as about 973 K and 1900 K, respectively. Radium has no stable isotope and has sixteen radioactive isotopes known to exist, with half-lives ranging from less than 1 millisecond (^{216}Ra) to 1620 years (^{226}Ra). One gram of the longest-lived ^{226}Ra undergoes 3.7×10^{10} disintegrations per second; this amount of radioactivity has been defined as one curie. Radium occurs in nature and is present in all uranium minerals in trace quantities.

Temperature Dependence

Although no information appears to have been published regarding the electrical resistivity of radium, a value of $0.186 \text{ W cm}^{-1} \text{ K}^{-1}$ attributed to Chirkin [87] for the room temperature thermal conductivity of radium does appear in the Handbook of the Physicochemical Properties of the Elements edited by Samsonov [88]. Neither the basis of this value nor its probable reliability is known.

We have roughly estimated the lattice thermal conductivity of radium at 293 K to be $0.013 \text{ W cm}^{-1} \text{ K}^{-1}$ by extrapolation to the atomic number 88 of a curve drawn through the lattice thermal conductivity values of calcium, strontium, and barium in a logarithmic graph of lattice thermal conductivity versus atomic number. The lattice thermal conductivity values of calcium, strontium, and barium are taken from Cook and Van der Meer [73]. Using the Wiedemann-Franz-Lorenz law, the electrical resistivity at 293 K is estimated to be $41 \times 10^{-8} \Omega \text{ m}$.

On the basis of the expected similarities between radium and other cubic-structure alkaline earth elements, namely calcium, strontium, and barium, we have roughly estimated the provisional intrinsic electrical resistivity of radium from 200 to 500 K by a least-mean-square-error fitting to the intrinsic electrical resistivity values of calcium, strontium, barium with a logarithmic equation with temperature and atomic number as the independent variables. The resulting equation is as follows:

$$\log_{10} \rho_i = -0.95 \log_{10} T - 1.18 \log_{10} Z + 1.37 \log_{10} T \times \log_{10} Z \quad (14)$$

where Z is the atomic number and T is the absolute temperature.

The provisional values are listed in Table 18 and shown in Figure 12. The uncer-

tainty in the provisional values is believed to be within $\pm 80\%$. The room temperature electrical resistivity value is about two times of the value calculated from Chirkin's thermal conductivity data.

TABLE 18. PROVISIONAL ELECTRICAL RESISTIVITY OF RADIUM
(Temperature Dependence)

[Temperature, T, K; Intrinsic Resistivity, ρ_i , $10^{-8} \Omega \text{ m}$]

| T | ρ_i |
|--------|----------|
| 200 | 44 |
| 225 | 54 |
| 250 | 65 |
| 273.15 | 76 |
| 293 | 85 |
| 300 | 88 |
| 350 | 115 |
| 400 | 145 |
| 450 | 177 |
| 500 | 212 |

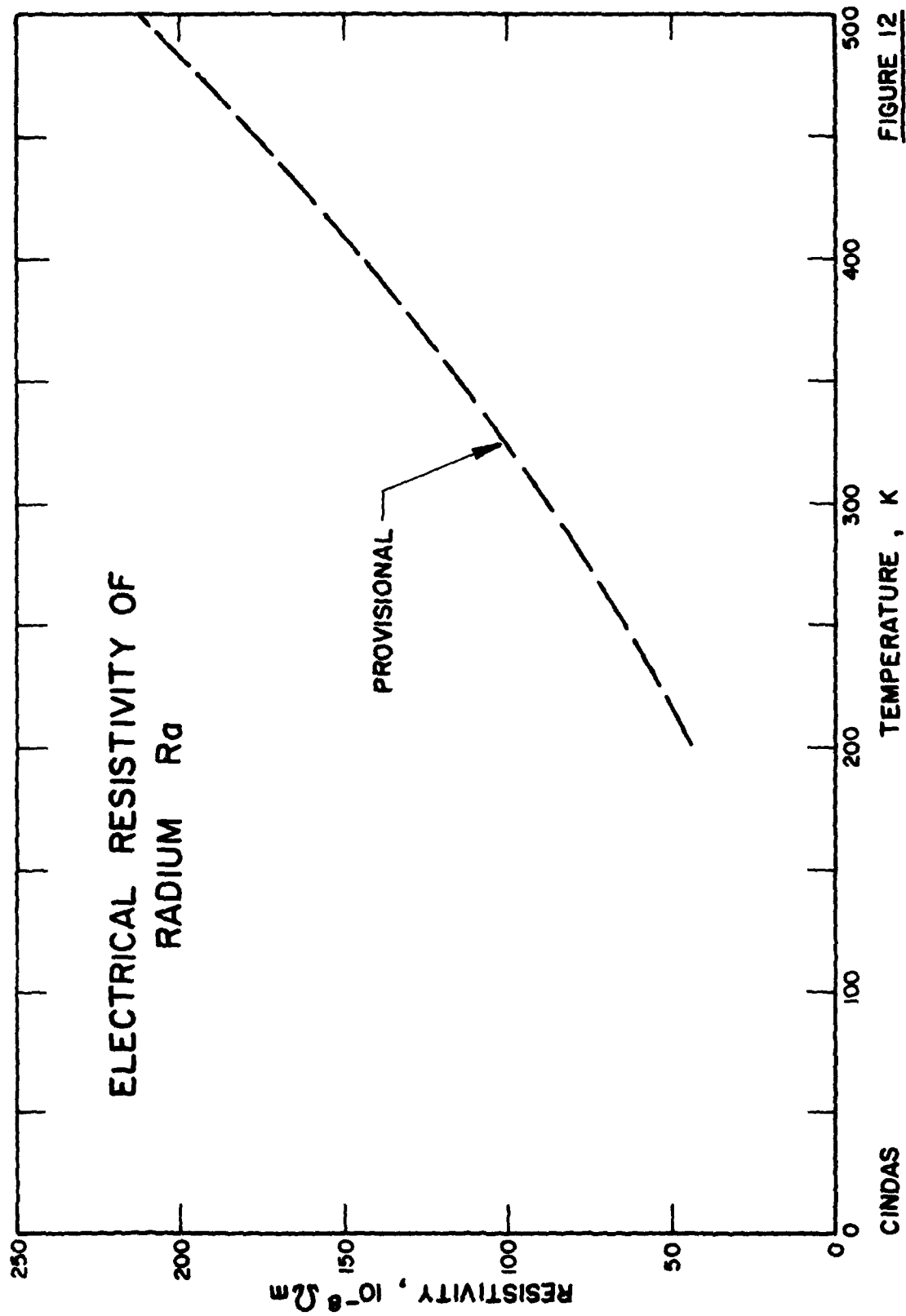


FIGURE 12

5. SUMMARY AND CONCLUSIONS

The electrical resistivities of alkaline earth elements have been surveyed and studied over the years by a number of investigators, including Meaden [89] and Cook, Laubitz, and Van der Meer [71, 73, 84]. Electrical resistivity data are presented also in a number of handbooks such as those of Kaye and Laby [90], Landolt-Börnstein [91], AIP [92], CRC [93], etc. However, their main concern is to provide a general picture by giving only one or a few particular sets of data, and only a limited temperature range is covered.

The purpose of the present work is quite different from that of the above mentioned works. There are two major aims: (1) to exhaustively search the open literature so that all the available experimental data are comprehensively compiled, and (2) to generate recommended reference values by critical evaluation, analysis, and synthesis of the existing experimental data. These aims are now achieved. This work has presented the most comprehensively compiled experimental data and information on the electrical resistivity of alkaline earth elements and has provided the recommended reference values over a very wide range of temperature. The recommended values were obtained by least squares fitting of the selected experimental data or by correlating the related properties.

A comparison of electrical resistivity data from the literature with the present recommended values are shown in Table 19. Table 19 shows that the recommended electrical resistivity values from the various sources are quite different, up to 100% in some cases, that the more recent values are not necessarily closer to the truth, and that many of the values contained in popular handbooks are much in error. This attests to the need of reliable reference values such as those generated in the present work.

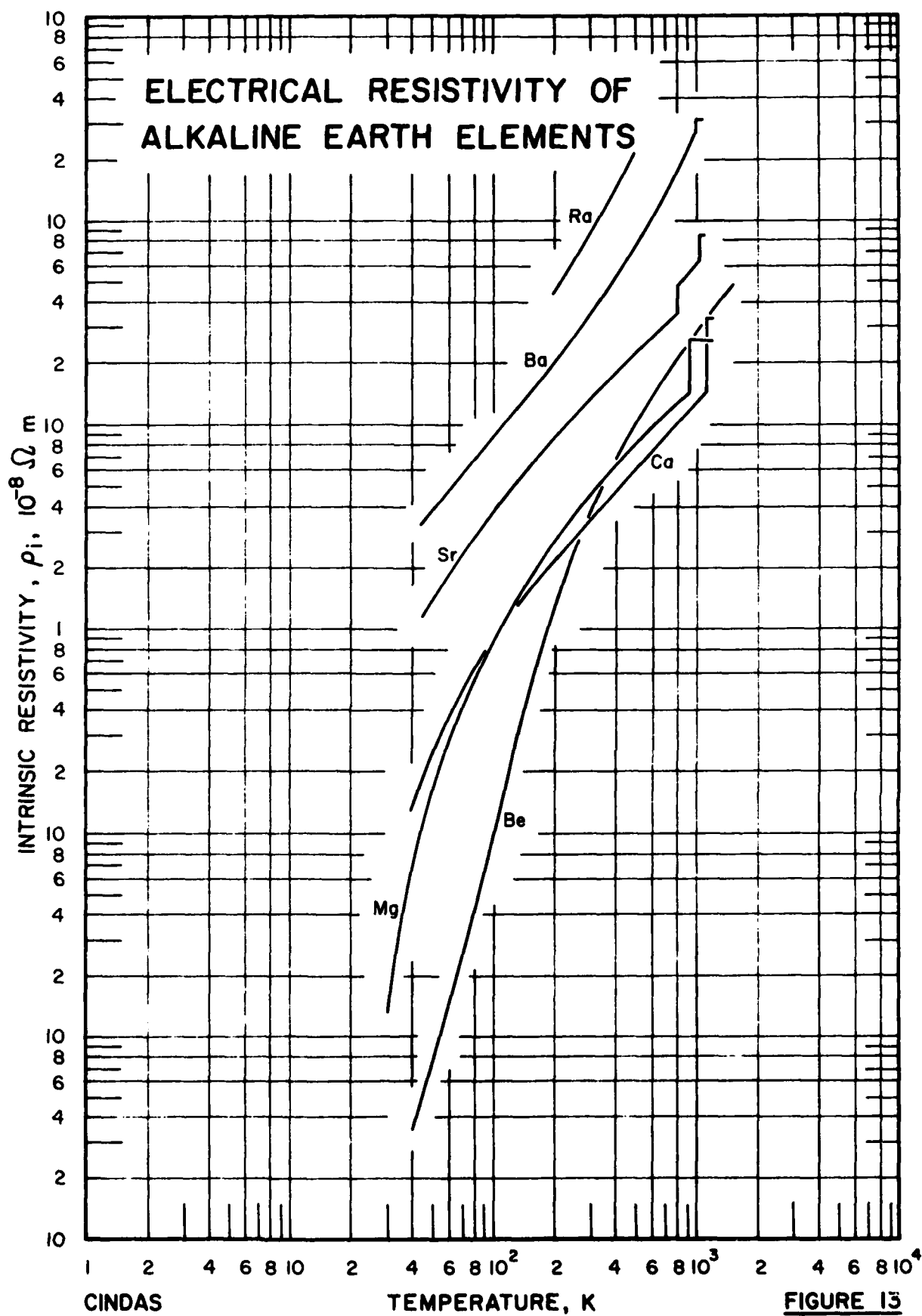
With a view to bring out any similarities or differences between the recommended values for the alkaline elements, the recommended values of the intrinsic resistivities for all the six elements are shown together in Figure 13. It can be seen from Figure 13 that the electrical resistivities of calcium, strontium, barium, and radium which have cubic crystalline structure, form a nice family of curves with systematic variations, those of heavier elements being the higher. The electrical resistivities of beryllium and magnesium, which have hexagonal crystalline structure, vary differently from the above mentioned and from each other. Their cross-over is due to the fact that beryllium has a much higher melting point.

TABLE 19. COMPARISON OF ELECTRICAL RESISTIVITY DATA FROM THE LITERATURE WITH THE PRESENT RECOMMENDED VALUES

| Element | Temperature K | Total Resistivity, ρ , $10^{-8}\Omega$ m | | | | | | |
|---------|------------------|---|---------------|----------------|--------------------------|------------------|----------------------------------|-----------------------------|
| | | Present work (1976) | CRC (1974) | AIP+ (1972) | Kaye & Laby (1966) | Meaden (1965) | Landolt & Börnstein (1960) | Cook, et al. (1973-6) |
| Be | 20 | 0.0336 | - | 0.0054 | - | 0.0054 | - | - |
| | 273.15 | 3.02 | 4.0 (293K) | 2.72 | 2.8 | 2.72 | 3.2 | - |
| | 1000 | 27.5 | - | - | 26 (973 K) | - | - | - |
| | 1500 | 49.9 | - | - | - | - | - | - |
| Mg | 20 | 0.0123 | - | 0.0125 | - | 0.0125 | - | - |
| | 273.15 | 4.05 | 4.45 (293 K) | 3.94 | 3.9 | 3.94 | 4.31 | - |
| | 922 | 14.7 | - | - | - | - | - | - |
| | 1200 | 25.6 | - | - | - | - | - | - |
| Ca | 20 | 0.0600 | - | - | - | - | - | 0.104 (30 K) |
| | 273.15 | 3.11 | 3.91 | 3.61 (293 K) | 6.8 | 3.6 (295 K) | 4.06 | 3.20 (277 K) |
| | 1000 | 12.8 | - | - | - | - | - | - |
| | 1150 | 33.0 | - | - | - | - | - | - |
| Sr | 20 | 0.918 | - | 2.48 | - | 2.48 | - | - |
| | 273.15 | 12.3 | 23.0 (293 K) | 21.8 | 23 | 21.8 | 30.3 | 12.5 |
| | 1000 | 62.2 | - | - | - | - | - | - |
| | 1093 | 84.7 | - | - | - | - | - | - |
| Ba | 20 | 0.940 | - | 0.98 | - | 0.98 | - | - |
| | 273.15 | 30.2 | - | 36.3 | 60 | 36.3 | 36.0 | 33 |
| | 1000 | 275 | - | - | - | - | - | - |
| | 1050 | 303 | - | - | - | - | - | - |
| Ra | 200 | 44* | - | - | - | - | - | - |
| | 273.15 | 76* | - | - | - | - | - | - |
| | 500 | 212* | - | - | - | - | - | - |

* Intrinsic resistivity

† The values in the AIP Handbook are taken from the book by Meaden so that they are identical.



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7. APPENDIX

7.1. Methods of Measuring Electrical Resistivity

A. Steady State Methods

1. Voltmeter and ammeter direct reading (V) [94*, p. 159, 119, pp. 244-5]
2. DC Potentiometric Method (A) [89*, pp. 151-8]
 - a. 4-probe potentiometric method
3. DC Bridge Method (B) [89, pp. 141-51]
 - a. Kelvin Double Bridge
 - b. Mueller Bridge
 - c. Wheatstone Bridge
4. van der Pauw Method (P), [95]*
5. Galvanometer Amplifier Method (G), [96*, pp. 159-62]

B. Non-steady State Methods

1. Periodic currents involved
 - a. Direct connection to sample
 - (1) AC Potentiometric Method (C) [89, pp. 161-2]
 - (2) AC Bridge Method (D) [89, p. 162]
 - (3) Q-Meter Method (Q)
 - b. No connection to sample
 - (1) Mutual Inductance Method (M) [97]*
 - (2) Self-inductance Method (S) [98]*
 - (3) Rotating Field Method (R) [99]*
2. Non-periodic currents involved
 - a. Direct connection to sample
 - (1) Transient (subsecond) technique (T) [100]*
 - b. No connection to sample
 - (1) Eddy current decay method (E) [101, 89, p. 103]

C. General Comments

1. Code "I" means Induction Method

This is a combination of Items B.1b. and B.2.b. above. Subsumed under I is M, R, S, or E. Used only if author indicates induction method used and does not report which specific one.

2. The symbol "→" is used if method described by the author is not sufficient to assign a specific code presently used. For example, if the author stated that "AC Method"

* References are given in Section 6.

was used in his measurement but no specifics were given, the following wording would be used in the column Composition, Specifications, and Remarks: "Experimental method described as an AC method." In the column for Method Used on the Specification Table the following symbol would appear: →.

